Status report for the CAST experiment and planned running in 2015

for the

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by the

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1 Introduction

Since it has started data-taking in 2003, CAST has successfully improved the limit on the axion-photon coupling constant for axion masses < 0.02 eV by a factor of 6 compared to previous axion helioscopes. Detector upgrades implemented within the last year, together with the second x-ray telescope line, will allow us to push this limit even further. In addition to axions, the results also limit the parameter space for axion-like particles (ALPS), which share part of its phenomenology. Axions, ALPS, and, more generally, Weakly Interacting Slim Particles (WISPs), are of interest for cosmology and astrophysics, since they have been proposed as candidates for dark matter and as an explanation for other astrophysical phenomena. Together with observational data, the limits on the coupling constant can serve as a consistency check of the various astrophysical and cosmological models. With our upgraded detectors, we expect to improve the signal sensitivity (for axion masses below 0.02 eV) by a factor of 4-5.

The CAST physics program is however not limited to solar ALP searches but points to several directions with the potential to cover a large sector of WISP searches.

In addition to studying axions and other ALPS, which are relevant as dark matter candidates, CAST is now launching a program to extend its reach also in the Dark Energy sector by attempting the detection of solar chameleons. These particles have a rest mass that depends on the surrounding energy density, an effect mediated by a direct coupling to matter. For the interior of the sun, the theoretical model for chameleons predicts their creation via the Primakoff effect. Likewise, they are expected to back-convert into photons in a strong magnetic field (such as in the CAST magnet) via the inverse Primakoff effect. The energy balance of the sun puts a limit on the rate of chameleon production in the sun, and thus the chameleon-photon coupling constant.

With a new detector (InGrid) recently installed on CAST, we have started an experimental search for chameleons and expect to eventually improve the solar limit on the coupling strength. Thus CAST has achieved a "first" as a chameleon helioscope with a SDD detector in the focal plane of the XRT telescope.

The direct coupling to matter of chameleon particles is the aim of a new a state of the art KWISP opto-mechanical force sensor, which enormous sensitivity (in the fN range) designed to detect the tiny pressure exerted by the flux of solar chameleons on a membrane surface. A measurement of the direct coupling to matter with KWISP, besides being a first and unique measurement of this kind, has the opportunity of simultaneously fixing a bound also for the photon coupling. The KWISP opto-mechanical sensor is in the commissioning stage and is expected to be online at CAST next year.

We have started investigating new detector concepts for relic ALPS. One idea, which was presented in the last SPSC report in 2013, involves the dish antenna concept. This approach, which has the potential of exploring the critical 1 meV region in axion mass, relies on the sensitive detection of mm waves and, being broadband, holds the promise of closing a large fraction of the current gaps in the axion (ALP) parameter space.

We are currently in contact with experts from MPE in Garching and the MPI in Bonn to study the feasibility of this concept for searching for axions in the mass range from 0.1 meV to 1 meV. Another approach to relic ALP detection inside the CAST magnet is based on the use of dielectric loaded resonators. Dielectric spacers in a waveguide (for example periodically spaced by some fraction of a wavelength) can optimize the coupling between the external magnetic field ad the electric field of the photo resulting from relic ALP "decay". This technology also holds the promise of extending the reach of CAST towards the 1 meV mass region.
Long and thin conducting cavities could also be inserted into a CAST magnet bore to act as relic ALP detectors. In this case the geometry of the waveguide can be designed in such a way as to optimize the magnetic-electric field coupling.

In the following, these topics are discussed in greater detail, along with the work done at CAST during the last year. We conclude our report with a summary of the physics potential of CAST itself, as well as its contribution as a testbed for technologies needed for next-generation helioscopes such as IAXO or other large Tokamak-like magnetic field structures.

CAST will become, with the implementation of the proposed physics program, the first true multi-approach laboratory for WISP physics.

2 Status report

2.1 Experimental area and detector development

2.1.1 End of running in 2013

The 2013 data taking started on 22nd September and ended on 7th December (76.5 calendar days). The data taking efficiency, in terms of solar trackings covered, was 82%.

The run ended several days early due to a failure in the cryogenics. When repaired on Tuesday 10th December the magnet warm up started in order to be $T_{mag} > 120^\circ$K on Friday 13th December –the shutdown date for the Cryo due to a 2 month shutdown for LS1 of the Cooling and Ventilation systems at LHC8. For the remainder of the shutdown, it was planned that the CAST magnet would slowly warm up.

2.1.2 Shutdown work and schedule for 2014

For the general CAST experiment, the 2013/2014 shutdown period was not particularly heavy; there were the usual maintenance of pumps and vacuum gauges and of the movement mechanisms. The chain clamps on all metal helico-flex seals were tested with a dynamometric spanner as done each year. There were no plans to open the cryostat, however the vacuum maintenance revealed a leak on the sealing plate joint of one of the four gate valves separating the detectors from the vacuum lines to the cold-bores inside the cryostat. The magnet had to be raised from 220K to 285K and the cold bores filled and purged with pure $N_2$ in order to remove the gate valve and send it for repair. The valve was then refitted and made operational.

The routine shutdown cryogenics maintenance was completed with only about one week delay. The vibration problems experienced by the main compressor last year have been investigated and new fixations and new bearings were installed. The estimate for the start-up of the cooling plant was for 8-10 April. The cryogenics actually started up on 9th April 2014 and reached 1.8K on the 24th April but stopped on the 30th April. Cooling power was lost due to a build-up of solid air contaminants blocking filters in the cold parts of the cold box. The air leak which caused this problem was eventually found on a pressure gauge near to the Roots pump (removed for recalibration and replaced but connection was leaking). Several weeks were then needed to purify the helium inventory of the system and regenerate filters and traps.

On the 4th June the pump down to 1.8K was started but stopped soon afterwards as there was still not enough clean gas in the clean circuit to function correctly. Two new problems were found; firstly a pressure regulator was set too high causing clean helium to pass via a pressure relief valve towards the...
storage balloons. Secondly, at least one of three cold valves which linked the cold box to the magnet was diagnosed to be not fully closing causing over-pressurisation with warm gas the MFB causing a loss of helium gas as liquid evaporated.

The two problems were eventually solved and the system set to bring the magnet to 4.5K then 1.8K with sufficient clean gas to ensure stable operation. The successive technical and logistical problems encountered by the cryo group delayed the CAST program by about 4 weeks. The problems of the cryo were in fact 7 weeks long but CAST was able to set up the theodolite/laser for XRT alignment at 1.8K and then make the alignment of the telescope and InGrid with the magnet slowly warming up during the problems.

The cryo group will review their maintenance and the handover from maintenance to operations procedures to avoid leaks in the system after maintenance. In view of the aging equipment, the cryo group will request a more thorough program of valve inspections and valve joint and seal replacement in the next shutdown. CAST is concerned about the lengthy delays occurring most years due to cryo start-up problems and have liaised with the cryogroup to try to ensure that new procedures are put in place so that start-up delays are minimised in future.

For 2015 run, CAST has requested that the magnet is stably operating at 1.8K for the 1st April 2015.

2.1.3 Sun filming

Twice a year it is possible to check the precision with which the magnet is pointing to the Sun, with a direct, visual method. It consists on taking pictures of the Sun in a special sun filming solar tracking run, with a camera with a telephoto zoom lens attached to the magnet. The camera is precisely aligned with surveyors help to the V1 bore of the magnet. Due to the difference in the propagation of axions and photons through the atmosphere, a correction to the magnet motion has to be applied.

Since the Sun filming is performed in the optical part of the electromagnetic spectrum it heavily depends on the atmospheric conditions. For example, in poor visibility conditions the results are of scarce quality or nonexistent. Furthermore the Sun filming can be performed only twice a year in a ten day

Figure 1: Moon filming on 16.03.2014.
long periods when the Sun is visible through the window in the experimental hall. Fortunately, in March the weather was good and we were able to have a set of very good pictures taken in five different days. Furthermore, in order to extend the filming period in order to depend less on atmospheric conditions a Moon filming possibility was explored. The tracking program was modified for this purpose and first pictures of the Moon were taken (see Figure 1). The problem with the Moon filming arises from the fact that the Moon passes in front of the window while being in different phases thus producing pictures that cannot be easily analysed due to the different visibility of the lunar disk in the sky.

For the alignment of the camera to the bore of the magnet, the usual procedure was used. Two irises were set with the help of the CERN surveyors (one in front of the camera, and the other one in a corner of the hall) and a laser light was shone through them in order to create an optical axis, parallel to the axis of the V1 bore.

This year the usual setup was used with addition of the possibility of remote focusing that helped to further improve the quality of the pictures (see Figure 2).

During the filming, the camera is controlled remotely from a PC, where it is possible to adjust the necessary parameters of exposure and sensitivity to make good quality pictures. These are taken as frequently as possible, around ten pictures per minute. After that, the analysis is done using the NI Vision LabView module for image analysis. In this analysis, the center of the Sun is extracted from every picture, along with the radius of the Sun and the goodness of the fitting analysis.

![Figure 2: Picture of the Sun taken with the new focusing system installed. An airplane passing in front of the Sun can be observed.](image-url)

The results of this campaign show that we are pointing to the Sun: approx. 3.5 mm in 10m ahead of the centre and 2.3 mm in 10m above it. Furthermore due to good atmospheric conditions and the quality of the pictures during two last campaigns year a trend in the deviation was observed (see Figure 4 and...
Figure 3: Data taken during the September 2014 campaign. A trend in the deviation can be seen. The September equinox takes place on the 23rd.

Figure 4: Deviation during the March 2013 campaign. A trend in the deviation can be observed. The point closest to the origin corresponds to data taken closer to Spring equinox.

For the moment the most plausible explanation to this deviation is an error in the alignment of the camera with respect to the V1 bore of the magnet. However, there is a tendency in the horizontal deviation
that depends on the filming date. If we exclude an error that is function of time in the pointing we can attribute it to the non linearities in the magnet movement, since the filming window corresponds to a zone where the movement of the magnet is highly nonlinear. Since, the reference checks done each day during the filming were stable and reproducible, there are things that we still have to understand.

2.2 Work on detectors

2.2.1 Sunset Micromegas

In the 2012 upgrade of the Sunset Micromegas, a scintillator veto with ~44% geometrical efficiency for cosmic muons was installed, producing a background reduction of around 25%. The promising results and the tests performed in dedicated experimental setups motivated the upgrade of the veto system. In September 2013, the newly-designed scintillator vetoes (see Figure 5) were installed in the Sunset line, providing a geometrical efficiency (without including production of secondary particles or quantum efficiency) for discriminating cosmic muons higher than 90%. The two sunset Micromegas took data with this configuration of passive and active shielding for around 75 days in 2013 (22nd September – 6th December) and 50 days in 2014 (6th July – 24th August), with 100% data taking efficiency, i.e. no sun tracking was lost due to Micromegas detector malfunction, remarking the high reliability of these readouts. The accumulated background during these periods results in an unprecedented level for a detector operated at surface. The scintillator veto system produced a background reduction of an extra 50%. The preliminary application of the discrimination criteria with 75% of signal efficiency for x-rays, the two Sunset Micromegas detectors present background levels of \((1.00 \pm 0.05) \times 10^{-6} \text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}\) in the [2-7] keV range.

Currently the Sunset Micromegas are dismounted due to the forthcoming installation of the ABRIXAS/MPE x-ray telescope, which needs to be aligned with respect to the magnet axis by means of a laser beam entering the magnet pipe from the sunset side.

![Figure 5: Left: Schematic view of the new scintillator cosmic vetos over the Sunset Micromegas. Right: Preliminary background energy spectra after applying the discrimination criteria of the 2014 data of the Sunset 1 detector. The spectra from the Sunset2 are very similar.](image)
2.2.2 Sunrise Micromegas and LLNL x-ray telescope

This year CAST has achieved one of the most important milestones of the current phase of the experiment: the installation, in the sunrise side of the magnet, of a new detection system combining a new x-ray telescope with an improved low background Micromegas detector. This system represents several “firsts” in axion physics. It is the first time an x-ray optics is designed and built specifically for an axion helioscope (and therefore optimized for the energies of the expected solar axion spectrum). This is also the first time the two techniques pioneered by CAST –x-ray focalization and low background techniques–, so far used in different CAST lines, are combined to join forces in the same system. The new detection line has thus become the one with the best signal-to-noise ratio in CAST (while final numbers must wait until data taking progresses, we roughly expect that focalization should improve the effective background in about a factor ~50 while reducing the efficiency in a factor of ~2 with respect the sunset Micromegas detectors). Very importantly, the new system represents the first time that technologies (both the optics and the detectors) proposed for the future IAXO are used in conjunction. The operation of this “IAXO pathfinder optics+detector system” will be an important milestone for the technical design phase of IAXO.

In the following, the new Micromegas detector setup for the focal plane, designed and built by the groups of the Universidad de Zaragoza and CEA/Saclay as a modified version of the successful design at operation in the sunset side, as well as the new x-ray telescope, designed and built by the groups of LLNL, DTU and University of Columbia, are described. Subsequently, the process of installation, alignment and commissioning in CAST during August and September is described, as well as the very first data taken.

**Figure 6:** Left: One of the new Sunrise Micromegas detector. The active area is situated on the left, while the strips’ signals are extracted from the central area on the right. The HV is fed by the lines situated on the right. Right: Uniformity of the gain of the new Micromegas detector. The dead areas (in purple) show lower values than the unity (in green) and lie outside the axion-sensitive area.
The new Sunrise Micromegas detector

During 2013, the Sunrise Micromegas detector was redesigned to improve its features in terms of shielding and gas chamber properties.

1) **Shielding**: Only two base materials, which are clean in terms of radiopurity, have been used: copper and Polytetrafluoroethylene (PFTE). The new chamber is all made out of copper, including the base on which the detector is supported. All gaskets are made of PFTE and the gas in/output are made of copper. Finally, the lead shielding thickness was increased to 5 cm, as in Sunset setup.

2) **Chamber properties**: a new field shaper was designed, printed on a flexible multilayer circuit and integrated in the chamber. This feature has made uniform the drift field, reducing the border effects. Apart from that, the high voltage connections were implemented in the detector printed board, which allowed an easy extraction of signals and voltages from the shielding.

However, during its operation in 2013, the detector experienced some problems. The main one was the bad isolation of the high voltage lines (the mesh and drift lines) to ground at the Micromegas printed board. These issues caused that only 6.5 hours of tracking and 90 hours of background were acquired. For this reason and for the integration with the LLNL telescope (LLNL-XRT), many components of the setup have been modified. We summarize the main changes in the following lines.

Three new detectors have been built, based on a new design which has moved the high voltage lines away from ground. One of them is shown in Figure 6 (left). The detectors were characterized before being installed, showing a larger optimum range of drift fields than the previous design and a good energy resolution. The best one in terms of gain uniformity (Figure 6, right) was installed at CAST.

From the electronics part, a new high voltage box has been built to include low frequency filters for all lines (Figure 7, left). In addition, the interface card has been remade to avoid any antenna coupling, replacing former jumpers by soldered resistors and including new flat cables (same figure, center). The Faraday cage has also been rebuilt to fit the new AFTER-based electronics, the High Voltage (HV) box and the preamplifier (same figure, right). Finally, a new cable tray has been installed for the signal and voltage cables.

**Figure 7**: Left: The new HV box, which includes the low frequency filters, created by the capacitors in yellow. Center: The new interface card. Right: the inside of the new Faraday cage. All the electronic components are screwed to the walls.
From the mechanical part, the complete vacuum line has been redesigned and built to fit the new LLNL telescope and to align both the telescope and Micromegas detector with the magnet. A schematic view is shown in Figure 8. Moreover, a new detector window has been designed, with smaller aperture, fitting the area of the focalization of the signal. It has a spider design with a central spot of 8.5 mm diameter, which is enough for the expected spot created by the telescope. A view of this pattern is shown in Figure 15 (left). Finally, a muon veto, formerly used at the Sunset side during 2012, has also been installed.

**Figure 8**: Design of the new vacuum line for the Sunrise-MM side. The labels in violet are the vacuum components that have been redesigned and built. In green, the MM detector, the LLNL-XRT and the existing gate valve.
The LLNL+DTU+Columbia X-ray optic

Overview
The new X-ray optic for CAST was made following the same techniques developed for NASA’s NuSTAR satellite mission. In this approach, flat-panel glass is thermally-formed (slumped) into cylindrical shapes. These curved pieces of glass are then deposited with multilayer coatings to enhance X-ray reflectivity. The coated substrates are then cut into conical (truncated cone) shapes and epoxied into a precision assembly that results in a reflective X-ray optic that approximate a Wolter I geometry.

Design and fabrication of the X-ray optic was performed by a team of researchers at LLNL, DTU-Space and Columbia University. Alignment and integration of the optic into the CAST experiment was performed by a larger team consisting of LLNL, DTU-Space and U.Zaragoza.

Design of the optic
For solar axion experiments, X-ray telescopes made from segmented glass substrates offer two distinct advantages, compared to integral-shell telescopes made via replication or from large glass/ceramic blanks. First, unusual, azimuthally asymmetric designs can be fabricated to minimize the amount of space required for vacuum lines and supporting hardware. Second, it is easy to deposit multilayer coatings optimized to maximize the X-ray reflectivity exactly at the peak of the axion spectrum, thus increasing the signal-to-noise and sensitivity.

The optical design had certain constraints due to the fact that we used the same infrastructure for the new CAST optic that was used to fabricate the NuSTAR telescopes. Specifically, each mirror substrate had a length of 225 mm, for a total telescope length of 454 mm (there is a 4 mm gap between the pri-
mary, parabolic-like mirror and the secondary, hyperbolic-like mirror). We also designed an optic that could be integrated into CAST without disturbing the location of the existing telescope and that would be compatible with a new Micromegas detector with a customized shielding configuration. This led us to fix the focal length to 1500 mm.

With these parameters determined, we then had to determine the radii, graze angles and multilayer coatings. We have previously published a paper in the Proceedings of the SPIE (Jakobsen, Pivovaroff & Christensen, Anders C. Jakobsen, "X-ray optics for axion helioscopes", Proceedings of the SPIE, Vol. 8861, 886113 [2013]) that describes in detail the optimization process. Here, we briefly discuss the procedure and present the results. Figure 9 is a photograph taken during the fabrication of the optic.

The basic premise behind the optimization is to make the coatings as efficient as possible where there will be most the detected photons, which is the product of the axion spectrum and the quantum efficiency of the Micromegas detector. Finally, the graze angle of the incident X-ray influences the multilayer coating design, since to first order, coatings will have reflectivity closer to unity the shallower the graze angle.

When all these factors are put into the optimization, the result in an X-ray telescope with 13 nested layers than span a 30 degree azimuthal section. The projected area of the telescope just overfills the 43-mm diameter bore of the V2 line. Table 1 lists the basic properties of the optic. Figure 10 shows effective area of the telescope as a function of photon energy.

Table 1: properties of segmented CAST x-ray telescope

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope design</td>
<td>Cone-approximation, Wolter 1</td>
</tr>
<tr>
<td>Focal length</td>
<td>1500 mm</td>
</tr>
<tr>
<td>Total telescope length</td>
<td>455 mm</td>
</tr>
<tr>
<td>Length, parabolic-like mirrors</td>
<td>225 mm</td>
</tr>
<tr>
<td>Length, hyperbolic-like mirrors</td>
<td>225 mm</td>
</tr>
<tr>
<td>Layers (or shells)</td>
<td>13</td>
</tr>
<tr>
<td>Substrates</td>
<td>Slumped glass, 0.21 mm thick</td>
</tr>
<tr>
<td>Total number of mirror segments</td>
<td>26</td>
</tr>
<tr>
<td>Area, magnet bore (43 mm Ø)</td>
<td>14.52 cm²</td>
</tr>
<tr>
<td>Area, clear aperture inside magnet bore</td>
<td>9.60 cm² (68.0% coverage of the magnet bore)</td>
</tr>
<tr>
<td>Coatings</td>
<td>Ir/B4C multilayers, 4 different recipes</td>
</tr>
</tbody>
</table>

Installation of the optics

The telescope was installed by team members from LLNL, DTU-Space and U. Zaragoza, with the assistance of CERN staff, from 30 August – 4 September 2014. A detailed description of the alignment procedures has been documented elsewhere. Here, we highlight some results obtained during installation and alignment.

Figure 11 compares a ray-trace simulation (left) of photons travelling through the magnet, reflecting through the optic and being stopped at a virtual plane at the exit aperture of the optics with an image of the exit aperture of the telescope, after it was installed on CAST and is being illuminated by a visible wavelength laser. The excellent agreement indicates the optic is well-aligned to the central region of the V2 bore.
After the telescope was aligned using the theodolite, the new Sunrise MicroMegas (SRMM) and shielding were installed. An Amptek Cool-X x-ray generator was installed on the MRB side of V2 along the bore axis, and once an operational vacuum level was achieved, it was turned on to illuminate the X-ray optic. After making a slight adjustment to the position of the SRMM such that the x-ray spot was centered in the middle of the detector, a long integration was acquired with the Cool-X. Figure 12 compares the SRMM data (left panel) with the ray-tracing results (center panel) and then overlays an intensity contour map generated from the ray-tracing results on top the SRMM data (left panel). There is excellent agreement.

The Cool-X data provides a good check on the angular resolution of the new XRT, and that data is consistent with the assumption that the optic has the same point spread function (PSF) of the NuSTAR telescopes. Specifically, we have assume a baseline model where the figure errors produce a PSF well-described by a narrow Gaussian core of 30 arcsec and a half-power diameter (HPD, sometimes also referred to as a full-width at half-maximum or FWHM) of 60 arcsec.
ferred to as the 50% encircled energy function (EEF) of 58 arcsec.

However, we have not yet performed a detailed calibration of the new XRT, and so to be conservative, for the purpose of defining the extraction region for the CAST science analysis, we will assume a PSF that is 1.3 times worse. Although this will result in a slightly higher estimate of the background, this conservative step also means we will not risk missing a putative signal. After the detailed calibration is performed, the analysis can be repeated with smaller extraction regions.

The new XRT was designed for maximum effective area (throughput), so it intentionally has a high degree of aberration for point-like sources. For solar axion searches, where the emission is assumed to arise from an extended region, the degree of aberration is effectively moderated.

To simulate the expected spot size, we modeled the emission region as a 3 arcmin diameter, located 1 A.U. from the CAST experiment, and assumed a solar axion differential spectrum given by the Bahcall, Pinsonneault, Raffelt, Serpico model of the form

$$d\Phi \propto \frac{E^{2.481}}{\exp(E/1.205)}$$

Millions of photons were ray-traced through the optic, and before the photons were registered on an infinitely large sheet at the focal plane position, we then accounted for the quantum efficiency of the SRMM. This is an important step since the PSF has energy dependence. Figure 13 plots the expected axion spectrum, detected with the new XRT+SRMM line.

![Figure 13: Axion spectrum, as measured by the next XRT+SRMM line.](image)

The red curve shows the normalized differential axion flux. The magenta curve is the SRMM QE, and the orange curve is the normalized XRT effective area (Effective Area divided by the geometric area of the magnet bore). The blue curve is the product of all three terms, and represents the expected spectral shape of a detection, before accounting for the finite energy resolution of the SRMM.

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With the ray-trace complete, we created a 2-dimensional histogram with 200 micron pixels to create an intensity map. This is presented in Figure 14. The rectangular shape results from the fact the clear aperture of the optic is only a 30° azimuth “wedge” of a surface of revolution. Traditionally, the x-ray
astronomy community has used circular extraction regions because of the circular symmetry of the PSF, for sources close to the optical axis. In our case, using circular extraction regions would result in missing “good” photons and introducing additional background noise. Instead, we should use rectangular extraction regions. Figure 14 also includes three candidate regions, each of which encloses approximately 50%, 70%, 90% and 100% of the total reflected signal. Table 2 presents the exact values of captured flux, as well as the geometric area.

<table>
<thead>
<tr>
<th>Fraction of flux captured</th>
<th>Geometric area [mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.3%</td>
<td>1.44</td>
</tr>
<tr>
<td>72.0%</td>
<td>3.08</td>
</tr>
<tr>
<td>90.6%</td>
<td>5.76</td>
</tr>
<tr>
<td>99.5%</td>
<td>13.6</td>
</tr>
</tbody>
</table>

Figure 14: Spatial extent of solar axion spot, imaged by the new XRT + SRMM. LEFT: False-color intensity map of the spot, where data has binned into 0.2×0.2 mm² pixels. The triangle indicates the center of mass. RIGHT: Same data as the left, now with four rectangular boxes indicating the extraction regions used in Table 2.
Commissioning of the LLNL-XRT/MM line

The LLNL telescope and the Micromegas detector were installed and aligned with the CAST magnet between the 25th August and the 4th September. First, the telescope was aligned with CAST magnet using a laser and plexiglass piece with a centering arrow, which represented the detector (Figure 15, left). This piece was then removed and the Micromegas detector was installed.

![Figure 15: Left: Spot from the collimated laser on the detector replica, 15 mm behind the focal plane. Center: Hitmap generated by the SR-MM detector when illuminated by a 55Fe source. The spider pattern of the new cathode window is clearly observed (the central circle is 8.5 mm diameter). Right: The spot created by the events coming from the x-ray finger at the other end of the magnet (about 13 m away) and focused by the LLNL telescope on the Micromegas detector.](image)

Its behaviour was then verified calibrating its surface by a $^{55}$Fe source. The hitmap generated by these data (Figure 15, center) shows the expected spider pattern of the new cathode windows. The Micromegas detector was then illuminated during one day by an x-ray finger installed at the Sunset side. This run has been used to delimit the expected spot created by axion x-rays, as shown in Figure 15 (right).

Finally, the lead shielding and the muon veto were installed and a new x-ray finger run was made to verify that the spot position was the same. The final setup is shown in Figure 16, indicating the different components.

Since the 4th September, the Sunrise Micromegas detector has been taking data in stable conditions in terms of gain, showing an excellent energy resolution of 13% FWHM at 5.9 keV (Figure 17, left), near the best value obtained with this kind of detectors. A preliminary analysis of the first 240 hours of background shows a level of $(0.8 \pm 0.2) \times 10^{-6}$ keV$^{-1}$ cm$^{-2}$ s$^{-1}$, which is compatible with the best background levels obtained in CAST by the Sunset Micromegas detectors. The background spectrum is shown in Figure 17 (right). These experimental parameters fit the expectations for the new line, given the few hours of data, and indicate that the physics goals set by the collaboration for the current vacuum phase can be achieved.
Figure 16: A view of the new Sunrise Micromegas + LLNL telescope line.

Figure 17: Left: Energy spectrum generated by the MM detector illuminated by a $^{55}$Fe source. Right: Energy spectrum generated after a preliminary analysis of the first 240 hours of background for the central region of the Sunrise detector. The different colors correspond to raw data (black) and events passing the different selection criteria: fiducial area (red), strips (magenta) and muon veto (blue).
2.2.3 InGrid detector and MPE x-ray telescope

InGrid detector

InGrid detectors are based on a Timepix ASIC, a pixelized readout chip, and a Micromegas mesh produced directly on top of the ASIC. The pitch of the sensitive regions is 55 µm. Already at moderate gas gains a very high efficiency can be reached and thus two important aspects for the physics reach in CAST can be fulfilled: A very good background suppression can be reached by exploiting the topological analysis of the events. Besides, a low detection threshold is possible by single primary electron counting. These two features were demonstrated in lab tests before. In 2014 a first test with the InGrid detector mounted on the CAST experiment was performed.

Detector test in the CAST Detector Lab

In April this year the improved InGrid detector was tested with the X-ray tube in the CAST detector lab. This test of the detector and the readout system served as a confirmation that the setup is ready for being used at the experiment.

Different combinations of X-ray tube targets and filter materials were used to obtain mostly monochromatic, characteristic X-ray lines between 8 keV and 277 eV (see Figure 18 for recorded spectra). The energy was determined by counting the primary electrons created in the photon conversion of the X-ray photons. These electrons are amplified in the gas amplification stage and detected on single pixels. Thus, counting the pixels receiving a signal above a certain threshold gives the energy in units of the average energy per ion pair (~25 eV). Even energies as low as the carbon Kα-line (277 eV) were visible and could be well identified (see Figure 19 for two example events).
All problems identified last year in a similar test were fixed and the only additional problem was the occasional hanging of the readout software, which could be fixed before later data taking (see next section) by switching to a different type of network adapter on the side of the DAQ computer. No problems with neither the detector nor the InGrid were identified. These tests lasted for one week and about 2,000,000 events were recorded corresponding to roughly four weeks of data taking at CAST.

Mounting the detector on the CAST experiment

When the XRT returned from the PANTER facility after its reflectivity was remeasured, the new vacuum line featuring a differential pumping scheme and safety interlocks were mounted at the downstream gatevalve of the XRT replacing the previous detector connected. After commissioning the vacuum system was tested and reached its nominal pressure value of less than $10^{-5}$ mbar within a few days. Then the XRT and the vacuum line up to the detector were aligned with the help of the laser system (see Figure 20). Finally, the detector itself was mounted. The alignment was verified with the help of the pyroelectric X-ray source (X-ray finger) at the other end of the dipole magnet. When the gate...

**Figure 19:** Two example events recorded with the InGrid detector: (left) 277 eV from the carbon $K_{\alpha}$-line, (right) 5.9 keV from the Mn $K_{\alpha}$-line.

**Figure 20:** Laser spot on a transparent disc with cross-hairs mounted behind the InGrid vacuum chamber. The laser is used to align the vacuum chamber to the optical axis of the X-ray telescope. The cross-hairs define the center location for the InGrid detector.
valves to the telescope and the cold bore of the magnet were opened, the image of the (weak) X-ray fin-
ger could be recorded over a period of 8 hours (see Figure 21).

![Figure 21: Reconstructed centers of events from the X-ray finger source (black bars indicating the central region of the InGrid)](image)

Figure 21: Reconstructed centers of events from the X-ray finger source (black bars indicating the central region of the InGrid)

Afterward the detector was operated for three weeks while the InGrid vacuum was isolated from the XRT. In this time the background at the experiment was studied. Following this the lead shielding designed and produced by the University of Zaragoza was installed and another week of background data was recorded. During this time the readout system performed continuously and without interference. Figures 23 and 22 show the setup before and after the lead shielding was installed.

![Figure 22: Vacuum system and InGrid detector mounted on the CAST experiment](image)

![Figure 23: Lead shielding placed around the InGrid detector.](image)

The data taken was analyzed with a likelihood method. In the course of the analysis the energy of the
event was determined by the total charge collected on all pixels of an event and a calibration curve deduced from the lab test. Then the event shape variables like length, width(rms) and eccentricity etc. were compared to events with similar energy taken in the detector lab before (see previous section) Depending on the result of the likelihood, each event was classified as photonlike or not. The cut applied on the result of the likelihood was adjusted for each energy regime to achieve a signal efficiency of close to 90%. Figure 24 shows the energy spectrum of the photonlike events collected during the 4 week period.

![Energy spectrum of photonlike events recorded with the InGrid detector, with and without lead shielding on the CAST experiment.](image)

**Figure 24:** Energy spectrum of photonlike events recorded with the InGrid detector, with and without lead shielding on the CAST experiment.

The general rate is about $10^{-5}$ hits per keV/cm²/s with three exceptions: At around 8 keV there is a significant peak presumably resulting from a combination of Cu Kα-line and cosmic rays passing through the detector perpendicular to the InGrid. There is also a line around 3 keV which is the irreducible Ar-Kα-line and finally at energies below 1 keV the number of electrons is so low, that topological properties can not be determined distinctly yet. Another tiny feature can be found at roughly 5 keV which corresponds to the Argon-Escape-Peak belonging to the 8 keV Cu Kα-line.

![Energy resolution of the InGrid detector in dependence of the gas gain for various gas mixtures(different ratios of argon to isobutane), all using a 4 micrometer thick silicon nitrite layer between the timepix chip and the Micromegas mesh.](image)

**Figure 25:** Energy resolution of the InGrid detector in dependence of the gas gain for various gas mixtures(different ratios of argon to isobutane), all using a 4 micrometer thick silicon nitrite layer between the timepix chip and the Micromegas mesh.
Determining best energy resolution

A master thesis (J. Ottnad) was done at Bonn, where the optimal electric field settings were studied to reach the best energy resolution. During these studies different gas mixtures of Ar: iC₄H₁₀ ranging from 99:1 to 90:10 were used. For larger fractions of isobutane energy resolutions of $\sigma_E/E \sim 3.85$ % were reached for $^{55}$Fe X-ray photons. For the gas mixture used in CAST (Ar:iButane 97.7:2.3), an energy resolution of $\sigma_E/E \sim 5.3$ % at 5.9 keV could be demonstrated (see Figure 25).

Decoupling the signal from the grid

Analog to the Micromegas approach also in the InGrid setup the signal of an X-ray photon can be read-out not only by a patterned anode, but it can be also decoupled from the amplification grid. This signal has no spatial information, but can be used to study either the energy of the signal, or the signal development with time. From this information additional separation power can be gained to discrimination background from X-ray photons. In particular the remaining cosmic ray tracks mentioned in 1.) could be largely suppressed. For this the decoupled signal was amplified and digitized with a very fast FADC. In the measurements the X-ray photons of a $^{55}$Fe were compared to the $\beta$-rays of a $^{90}$Sr source. It was found that the rise time had the most significant difference and could be well used in the analysis (see Figure 26). The current setup can however not be used in CAST. A modified version including an amplifier integrated in the setup needs more time for development and is planned for the next running period.

![Figure 26: Difference in the rise time of X-ray signals and track signals for the InGrid detector.](image-url)
MPE x-ray telescope

The MPE x-ray telescope has been used until last year as a focusing optics for the CCD detector and is now used for the new InGrid detector. The telescope is a spare module from the ABRIXAS mission and consists of six focusing segments, of which one is used in CAST to focus the x-rays coming from the dipole magnet onto the detector. It uses a set of parabolic and hyperbolic shells to focus the x-rays by double reflection at grazing and it has a focal length of 1.6 m. The effective area of the whole telescope is 83 cm$^2$ as measured in 2008. For CAST, the magnet pipe covers only part of one of the 6 telescope sectors, corresponding to an effective area of 10.5 cm$^2$. Still, so by focusing the x-rays with the telescope, the sensitivity of the detector can be increased by several orders of magnitude.

For the telescope to be effective, it is essential that the inner surfaces of the telescope are very clean, since a contamination by hydrocarbons can lead to significant absorption losses during the reflection. To ensure that the telescope is still working properly, it is therefore necessary to test its reflectivity every few years. Two measurements had been carried out so far: one in 2000 before the insertion of the telescope into CAST, and one in 2008 after several years of operation. After the measurements with the CCD detector had been completed in the autumn of 2013, the telescope has therefore been taken out for new reflectivity measurements to validate the CCD measurements from 2008 - 2013 and to check its status before installing the new InGrid detector.

Like the two measurements before, the reflectivity of the telescope was checked at the PANTER facility operated by the Max-Planck Institut für extraterrestrische Physik in Munich. PANTER is used regularly to check x-ray optics for space missions and is therefore ideally suited for this kind of measurements. Figure 27 shows a schematic of PANTER and of the x-ray source used in the measurements. The optics that are to be tested are installed in a 12 m long vacuum chamber, which is located 120 m away from the x-ray source. In the x-ray source, electrons are accelerated with a high voltage and hit a target, resulting in the emission of x-rays, the wavelength of which is determined by the target material. The x-ray source is about 1 mm in diameter, resulting in an angular resolution of 1" for the measurements.

For the measurements, the inner shells of the x-ray telescope were mounted in the vacuum chamber at PANTER (see Figure 28). Three x-ray detectors were available at PANTER for measurements:

1) A proportional counter (PSPC), with a field-of-view of 80 mm in diameter and a pixel size of 11 \cdot 11 \mu m^2

2) A CCD detector (TRoPIC) with a field-of-view of 19.2 \cdot 19.2 mm^2 and a pixel size of 75 \cdot 75 \mu m^2

3) A CCD detector (PIXI) with a field of view of 26.8 \cdot 26 mm^2 and a pixel size of 20 \cdot 20 \mu m^2.

The three detectors are shown in Figure 28.

In a first step, the point spread function at 1.49 keV was measured by imaging the source onto the detector placed in the imaging plane. Within the margin or error of the measurement, the unchanged from the previous measurements in 2000 and 2008.
In the next step, the effective area of the telescope was measured. To determine the effective area, the source is imaged onto the detector, which is placed out of focus. This is illustrated in Figure 29, where the image created by the telescope is shown.

The measurements have shown a slight reduction of the effective area for low-energy X-rays. Figure 30 shows the results of the new measurements and compares it to the results from 2008 and the design values (marked as "Theory" in the plot). Compared to the 2008 measurements, the effective area for x-rays below 2 keV has decreased by about 5%. This moderate degradation is caused by additional hydrocarbon adsorption in the time since the last measurement. For energies above 2 keV, there is no detectable difference in reflectivity compared to the 2008 results. Both curves (2008 and 2014) are slightly below the theoretical design values, but no large degradation of the telescope has taken place.

**Figure 27:** The PANTER setup in Munich. (Left) Schematics of PANTER together with an aerial overview. The x-ray optics are mounted in a vacuum chamber which is 120 m from the x-ray source. (Right) Schematic of the x-ray source used in PANTER. By varying the electron-target setup, energies from 180 eV to 40 keV can be created. The x-ray source has a diameter of ~ 1 mm, corresponding to an angular size of about 1".

In the next step, the effective area of the telescope was measured. To determine the effective area, the source is imaged onto the detector, which is placed out of focus. This is illustrated in Figure 29, where the image created by the telescope is shown.

The measurements have shown a slight reduction of the effective area for low-energy X-rays. Figure 30 shows the results of the new measurements and compares it to the results from 2008 and the design values (marked as "Theory" in the plot). Compared to the 2008 measurements, the effective area for x-rays below 2 keV has decreased by about 5%. This moderate degradation is caused by additional hydrocarbon adsorption in the time since the last measurement. For energies above 2 keV, there is no detectable difference in reflectivity compared to the 2008 results. Both curves (2008 and 2014) are slightly below the theoretical design values, but no large degradation of the telescope has taken place.

**Figure 28:** Setup for calibration measurements at PANTER. (Left) X-ray telescope mounted in the PANTER vacuum chamber. (Right) The three x-ray detectors that are available: PSPC, TRoPIC, and PIXI.
In the measurements carried out in 2008, only characteristic emission lines were used as x-ray sources in the measurements. In the measurements carried out in 2014, a continuum x-ray source was used in addition, resulting in a much better energy resolution of the measurement. Figure 31 shows the results for both the continuum measurement and the measurement using emission lines in comparison to the theoretical curve. Clearly visible is the good performance of the telescope for x-ray energies below 2 keV.

After the measurements at PANTER had been completed, the telescope was transported back to CERN. It was installed back into the CAST setup in April and May 2014. After the telescope had been installed and its optical axis had been aligned to the optical axis of the magnet, the InGrid detector was connected to the telescope. This also involved extensive modifications of the vacuum system to accommodate the new detector.

After the vacuum system had been run for 2 months separated from the XRT and for 8 hours with the gate valve opened to carry out an X-ray finger run, it was discovered that for the assembly of the vacuum system a silicone based vacuum grease had been applied to all of the Viton joints. While this is common practice in vacuum technology, it has not been used at CAST due to the requirements concerning cleanliness of the vacuum in order to avoid deposition of molecular layers on the mirrors of the XRT. The silicone based grease in fact (partly) evaporates in the vacuum and can lead to this kind of molecular contamination and layers on all surfaces which degrade the reflectivity of the XRT mirrors. Therefore, the system was disassembled and all parts in contact with the grease are being cleaned or replaced.

Figure 29: Effective area: general view with the 6 sectors of the telescope with the out of focus transmitted intensity. The white circle marks the section of the telescope that has been used for focusing in CAST.
Measurements of the contaminated parts of the vacuum system showed traces of silicone at levels ranging from $2 \cdot 10^{-7}$ to $1 \cdot 10^{-6}$ g/cm$^2$. Since it was unclear at this point whether the telescope had also been contaminated, it was decided to take the telescope out of CAST again and to ship it to the MPE in Munich, in order to test the inner surfaces of the telescope for contamination. The tests carried out at MPE showed a hydrocarbon contamination level of $6 \cdot 10^{-8}$ g/cm$^2$. It was concluded that the telescope had not been contaminated and the telescope was shipped back to CERN for installation. The whole setup is planned to be reassembled and reinstalled in early October and measurements are planned throughout October and November.

Figure 30: Effective area 2008 to 2014 comparison: - no significant changes for energies $\geq 2$ keV; - approx. 5% loss for energies $< 2$ keV due to contamination (expected)

Figure 31: Characterization of effective area. Shown are measurements using discrete emission line sources and measurements using a continuum source.
2.2.4 Radiation pressure sensor for solar chameleons (KWISP)

The assembly, testing and measurements on the KWISP opto-mechanical force sensor designed for the detection of the radiation pressure from solar Chameleons on a nano-membrane are proceeding at the INFN Trieste Laboratory.

In such a membrane-based opto-mechanical sensor a Fabry-Perot (FP) optical resonant cavity is frequency-locked to a laser beam using an electro optic feedback (G.Cantatore et al., Rev. Sci. Instr. 66, 2785 (1995)). The feedback acts on the laser so that the instantaneous distance between the cavity mirrors, left “free” to float, is always a half-integer multiple of the laser wavelength. When the cavity is at resonance, its normal modes are not perturbed if a thin transparent membrane, is aligned and positioned near a node of the standing intra-cavity electric field. A subsequent membrane displacement couples the membrane mechanical modes to the TEM modes of the cavity, detuning mode proper frequency with a typical oscillatory dependence on membrane position along the cavity axis (M.Karuza et al. New J. of Phys 14 (2012) 095015). The sensor is calibrated by determining its detuning curve. Using the membrane mechanical characteristics, the curve can be expressed in terms of the force acting on the membrane. With this technique extremely tiny forces can be detected (in the fN range and below). The tests have now entered the critical phase of membrane insertion and alignment.

The main activities carried out so far and in progress are:

I) initial sensitivity estimate ( \( S_{\text{force, proj}} = 5.0 \times 10^{-14} \, \text{N/} \sqrt{\text{Hz}} \) ), assembly and alignment of the sensor (done)

II) Fabry-Perot cavity finesse measured, \( F \approx 60000 \) (done)

III) accelerometer measurements at CERN and in Trieste (done)

IV) vacuum and optics mechanical support upgrades (done)

V) membrane insertion, alignment and calibration (in progress)

I) The force sensitivity of the sensor was estimated, from preliminary measurements, to be \( S_{\text{force, proj}} = 5.0 \times 10^{-14} \, \text{N/} \sqrt{\text{Hz}} \), and subsequently a Fabry-Perot optical resonant cavity was assembled in an initial configuration using a vacuum chamber already available in Trieste

II) The Fabry-Perot cavity (85 mm long, two high reflectivity, 1/2 inch dia., 50 mm curvature radius, dielectric mirrors) was locked to the beam from Nd:YAG CW laser at 1064 nm by means of an active feedback (Pound-Drever-Hall locking technique) and the finesse was measured to be 59000, comparing well to the 60000 nominal value expected from mirror characteristics.
III) Accelerometer measurements were done both at CAST, on the sunrise end of the magnet where we plan to install the sensor, and in the Trieste laboratory. In Trieste peak accelerations of $\sim 7 \times 10^{-6}$ g occur around 100 Hz, while on the CAST magnet we find peak accelerations at around 25 Hz (and higher harmonics) of about $1.7 \times 10^{-2}$ g, with the magnet stationary, and $5 \times 10^{-2}$ g with the magnet moving. We are investigating options to isolate against mechanical vibrations. See Figure 33 for sample accelerometer spectra.

IV) The sensor vacuum chamber was upgraded with a clamping base allowing secure attachment to the optical bench, and equipped with vacuum gauges covering the pressure range from atmosphere to $10^{-10}$ mbar. A preliminary base residual pressure of $10^{-5}$ mbar was measured under turbo pumping. The cavity mirror support base was redesigned and rebuilt in the Trieste machine shop to center it inside the vacuum chamber.

V) The upgraded sensor assembly has been reinstalled on the optical bench and has being realigned with the laser beam and the injection optics. The finesse was checked and found to be consistently
The tests have now entered the critical phase of membrane insertion and alignment. The nano-membrane must be inserted at the center of the cavity and aligned perpendicular to the cavity optical axis. In this position the cavity original resonant modes are undisturbed. The membrane must then be rigidly displaced along the cavity axis and changes in the frequency of the resonant modes must be mapped against its movements. This mapping gives the sensitivity of the sensor to membrane displacements caused by an external force acting on it.

Insertion tests were started with a (5 mm)x(5mm) membrane (100 nm thickness). Comparatively large-area membranes have the advantage that for a given pressure (for instance the pressure from solar chameleon direct hits) the resulting force is larger and therefore easier to detect. Figure 35 below shows a photograph of the (5 mm)x(5mm) membrane mounted a holder (at left) and of the manually actuated tilting stage used to pre-align the membrane before evacuating the chamber (at right).
2.3 Data taking, analysis and publications

2.3.1 Solar axion search

In 2013 a new vacuum phase started with an improved sensitivity. The 2013 data taking campaign began on the 22\textsuperscript{nd} September and was completed on the 7\textsuperscript{th} December. The data taking efficiency, in terms of solar trackings covered, was 82\%. The detectors used in this period were three Micromegas detectors (two in the Sunset and one in the Sunrise side) and one SDD detector on the Sunrise side. Unfortunately the Sunrise Micromegas detector with a novel design, showed some problems (see Section 2.2.2) that delayed its commissioning and at the end only one week of tracking data was acquired. For this reason new Micromegas detectors have been manufactured this year with an improved design (see section the new Sunrise Micromegas+LLNL telescope). Nevertheless, due to the improvement of the background levels in the sunset Micromegas detectors, CAST has slightly surpassed its previous published vacuum limit (see Figure 37) at a preliminarily estimated level of $g_{a\gamma} < 8.40 \times 10^{-11}$ GeV\(^{-1}\) at a 95\% of CL for axion masses $m_a < 0.02$ eV, this limit has been obtained by computing only the Sunset data of the 2013 campaign.

The data taking program of the vacuum phase started in 2013 resumed in 2014. The data taking started on the 3\textsuperscript{rd} of July with only the two Sunset Micromegas detectors were taking data. It was stopped on the 25\textsuperscript{th} of August to allow the installation of the new LLNL x-ray telescope (XRT) with a novel Micromegas detector in its focal plane. The installation of the new system (see Section 2.2.2) was successful and the data taking restarted on the 11\textsuperscript{th} of September. Until the end of September, only the LLNL XRT + Micromegas system is taking data. It is then that the installation of the Ingrid detector in the focal plane of the MPE XRT is planned, together with the mounting of the two Sunset Micromegas detectors. After this intervention the data taking is expected to continue until the 17\textsuperscript{th} of November with all the detectors in operation. The data taking efficiency for the period 3\textsuperscript{rd} of July to 25\textsuperscript{th} of August was 94\%.

Part of the results of the full \textsuperscript{3}He phase (2008-2011) of CAST have already been published [1], in which the data of the three Micromegas detectors were used to derive the coupling limit. A new publication including the CCD data is about to begin.

Another publication is being prepared and is in an advanced state, with the data taken in 2012. During 2012 the \textsuperscript{4}He phase was re-scanned, partially motivated by the improved background in the Sunset Micromegas detectors. Two different regions were scanned: one narrow band around $m_a \sim 0.4$ eV, reaching the KSVZ line and above $m_a \sim 0.2$ eV, by covering a “suspicious step” (see Figure 36 for more details). The data of the three Micromegas detectors have been analyzed: the absence of any signal above the background leads to a limit on the coupling constant of $g_{a\gamma} < 1.5 \cdot 10^{-10}$ GeV\(^{-1}\) at a 95\% of CL.

Figure 36: Top: Preliminary exclusion regions in the $m_a$-$g_\alpha$ plane of the CAST results during the 2012 $^4$He phase. The black and the red lines are the previous results of CAST with $^3$He and $^4$He respectively, while the blue line is referred to the scanned region during 2012. Bottom: Expanded view of the preliminary limit for the 2012 $^4$He phase, two different figures are displayed: on the left the suspicious step at $m_a \sim 0.2$ eV and on the right the scanned narrow range about $m_a \sim 0.4$ eV.
2.3.2 X-ray CCD

The analysis of the He-3 data taken with the CCD is progressing and will be finished by the end of 2014. The raw data for the years 2009-2011 have been filtered and noisy intervals, caused by signal contamination from ambient light and other glitches, have been removed. The raw data have been merged to daily, weekly, and yearly files, and the control data from the slow control system (monitoring the status of the vacuum system, cryogenics, etc.) and the tracking data (monitoring the magnet orientation relative to the sun) have been merged with the CCD data. Based on the data from the slow control system and the tracking data, the time intervals for the background measurements and the solar tracking periods have been identified.

Based on these "good time intervals", event files have been created from the raw data. In the event files, valid events, that is signal patterns that can be caused by x-rays, have been identified and event lists have been created. These sort the events, based on how many pixels registered an individual event, into five lists: single pixel events, double pixel events, triple pixel events, quadruple pixel events, and a list collecting all valid events. All events that are not created by x-rays were collected in a separate list for cross-checking.

Figure 37: Preliminary results of the ongoing vacuum phase with the two Sunset Micromegas detectors. The blue represents the previous CAST published results from 2003-2004, the black line the preliminary results using the 2013 data from the sunset Micromegas, and the brown-filled area the approximate sensitivity to be reached with the data taken until the 25th of August (currently under analysis), while the red line are the prospects for the full data taking phase with all detectors.
Figure 38 shows as an example the events registered on the CCD integrated over all measurements in 2009. No indication of an axion signal is discernible in the image. Figure 39 shows the light curves for 2009, that is the signal rate on the chip for the different energy bands. The data show the statistical variation of the background signal, but no spike caused by axions. Currently, the data analysis is being cross-checked to ensure that the data has been processed correctly. Once the cross-checking has been finished, the CCD data for the years 2009-2011 will be added to the data from the other detectors, resulting in an improved limit for the the axion-photon coupling constant.

Figure 38: Shown are the events recorded on the CCD in the year 2009. The data cover the pressure steps from step 420 through step 667, a total of 21 weeks and $1.6 \cdot 10^{11}$ frames. The image covers all events in the energy range from 0.5 - 14 keV. The color coding is as follows: Red events: 0.5 - 1 keV; Green events: 1 - 7 keV; Blue events: 7-14 keV. The two red lines in the image are caused by defects of the CCD.
Figure 39: Light curves for the 2009 CCD data. Shown are the rates all events with an energy above 0.5 keV, given in counts per second and using a 0.5 day binning.
2.3.3 CFD simulations

The computational fluid dynamics (CFD) simulations that are carried out in collaboration with the CFD team of EN/CV aim to understand the density distribution in the magnet bores, which cannot be determined experimentally and which affects the axion-photon conversion probability significantly.

By using the measured pressure of He-3 in the cold bores and the magnet temperature, CFD simulations calculate the density profile of He-3 and predict the pressure change during the tilting of the magnet. After years of running extensive simulations and having tried several fluid dynamics models, the simulations are finalized for the He-3 data.

Laminar flow was chosen for the horizontal case, which can be considered a conservative approach that shrinks the gas volume with constant density. When the magnet is tilted, the asymmetry in the system enhances the natural convection in the lower parts, and a combined model called “half laminar” was chosen where laminar flow is only imposed in the upper half of the magnet bore, and the lower extremity is solved with a SST k-ω turbulence model. The combination of these two models succeeds in reproducing the pressure change when tilting the magnet.

As the work is finalized, the results on details of the CFD simulations will soon be presented in a paper submitted to “Journal of Heat and Fluid Flow”.

Figure 40: Pressure change between horizontal and tilted (-6deg) cases for various pressures. The choice of laminar model in horizontal case and half-laminar model in tilted case gives the best result. Right: Pressure change during tilting the magnet from -6 to -1 degrees at 84mbar. Y axis shows the comparison with the -6 degrees.
On the physics side, one can make use of the simulations to determine the effective coherence length inside the magnetic field (see Figure 41), which is interesting for axion physics. The parts with rapidly decreasing density in the extremities of the cold bore are not taken into account in the calculations.

### 2.3.4 Chameleon search with a SDD

Chameleons are dark energy candidates to explain the accelerated expansion of the Universe. Their main characteristic is that their effective mass depends on the energy density of the environment. They can be created by the Primakoff effect in the presence of a strong magnetic field and can be converted to X-ray photons in CAST via the inverse Primakoff effect (like axions) [1].

In 2013 CAST began to search for these dark energy particles. For this program, a windowless silicon drift detector (SDD) was chosen with high quantum efficiency, good energy resolution and a relatively large area. The detector collected 15.2 hours of tracking data and 108 hours of background in the energy range of interest from 400-1500 eV. The result of the data analysis is compatible with the null hypothesis. Figure 42 shows the expected number of counts in our detector, the subtracted counts (tracking - background) and the best fit to the data. The compatibility of the data with the absence of excess of X-rays allows the derivation of a preliminary limit to the chameleon to photon coupling constant, over a range of $\beta_m$ from 1 to $10^6$ (Figure 43):

$$\beta_\gamma \leq 9.20 \times 10^{10} \text{ at } 95\% \text{ C.L.}$$

Figure 42: The expected number of photons from chameleon conversion inside the CAST magnet, that reaches the SDD is calculated from the theoretical photon spectrum arriving at the detector, from the conversion of chameleons, taking into account the total tracking time, the quantum efficiency of the detector and its area, the magnetic length that the chameleons travel inside CAST, and the absorption phenomena on the cold surface of the SDD due to the absence of window.

Figure 43: Constraints on the coupling of the chameleons to matter and photons [2]. The current constraints are shown as shaded regions and the future ones as solid lines. The preliminary result of CAST appears as a solid purple area. The black dashed line shows the solar limit whereas the dashed purple one shows the actual limits of sensitivity of CAST.
3 Proposal for 2014-2015

3.1 Physics case

3.1.1 Solar axions and ALPS

CAST carried out phase I, with vacuum in the magnet bores, in 2003 and 2004. The limit obtained to the axion-photon coupling \( g_{a\gamma} < 8.8 \times 10^{-11} \) GeV\(^{-1}\) (for \( m_a < 0.02 \) eV) is now widely known and referenced by the community. This value represents a factor of 6 in \( g_{a\gamma} \) better than the previous axion helioscope (which translates into a factor of \( \sim 10^3 \) better in the detectable signal strength -number of counts-). Although vacuum operation of CAST does not provide sensitivity to QCD axion models (because of the lack of coherence for \( m_a > 0.02 \) eV, this being the motivation for phase II), the possibility of pushing CAST vacuum limit to lower \( g_{a\gamma} \) values is also highly motivated, both theoretically and observationally. These motivations were explained in detail in our proposal to SPSC in 2012 [1]. While we refer to that document for a complete description and a proper account of references, we will only briefly review them in the following points:

1) A whole category of particles called axion-like particles (ALPs) or, more generically, weakly interacting slim particles (WISPs), is often invoked in several scenarios, theoretically well motivated. Although not necessarily related with the axion, they share part of its phenomenology, and therefore they would be searchable by similar experiments. ALPs often appear in extensions of the standard model (SM) as pseudo Nambu-Goldstone bosons of new symmetries broken at high energy. But most interestingly, string theory also predicts not just one ALP, but in most cases a rich spectrum of them (including the axion itself). Remarkably, the region of the ALP parameter space corresponding to the first orders of magnitude just below the current CAST bound in \( g_{a\gamma} \) correspond to intermediate string scales and are specially motivated as they would contribute to the natural explanation of several hierarchy problems in the SM.

2) There is a possible connection between ALPs and dark matter (DM). Recently it has been noted that the non-thermal production mechanisms attributed to axions are indeed generic to ALPs (and to any bosonic WISP). The range of ALP parameters including ALP models possibly solving the DM problem gets substantially enlarged both in \( g_{a\gamma} \) and \( m_a \) and in particular includes part of the region that an improved CAST vacuum run could probe.

3) A number of unexplained astrophysical observations may indicate the effects of an ALP. They must be treated with caution because usually an alternative explanation using standard physics or an uncontrolled systematic effect cannot be ruled out. One of them is the observation of very high-energy photons with directions correlated with very distant sources, apparently incompatible with the expected opacity of the intergalactic medium at such energies. Different scenarios invoking photon-ALP oscillations triggered by intervening cosmic magnetic fields have been invoked by several authors to account for the unexplained observations. For some of these cases, ALP parameter \( g_{a\gamma} \) lie just beyond the best current experimental limit from CAST. Any improvement beyond the current CAST vacuum limit will imply that part of this parameter space region would be probed.

Technologically, CAST has now the possibility to operate in vacuum with increased sensitivity compared with our 2003/04 runs, based on recent ideas and developments that we are putting forward in the context of IAXO (the International Axion Observatory), the future axion helioscope whose Letter of Intent was submitted to the SPSC in 2013 [2]. The ongoing vacuum run in CAST will test technological
options that are proposed for the large-scale effort represented by IAXO. Two of the innovations in which CAST success has relied on are the use of x-ray focalization to increase the signal-to-noise ratio, and the use of low background techniques to reduce the detector backgrounds. The first strategy is exemplified by the CCD+ABRIXAS telescope detection line, while the second one by the other 3 detection line based on low background Micromegas detectors. The new sunrise system (the new Micromegas+LLNL telescope) will combine both strategies in the same system: a new x-ray optics coupled to a low background Micromegas detector. The implementation of this concept in CAST will not only increase the signal-to-noise ratio of the sunrise Micromegas, and the sensitivity of the experiment, but would serve as a pathfinder project to test the technological options being proposed to build large scale, cost effective, x-ray optics with customized parameters for the future IAXO.

The physics potential of the ongoing data taking campaign in terms of sensitivity in the ALP \((g_{a\gamma} - m_a)\) plane is plotted in Figure 44 for a variable exposure time of the experiment. As shown, CAST could improve the current vacuum result down to \(g_{a\gamma} \sim 6 \times 10^{-11} \text{ GeV}^{-1}\), corresponding to a factor 4-5 improvement in the detectable signal strength. This result would probe deeper into the unexplored ALP region motivated by the theoretical, cosmological and astrophysical arguments mentioned above.

[1] CERN-SPSC-2012-028

**Figure 44**: Expected sensitivity to \(g_{a\gamma}\) of the ongoing CAST vacuum phase with all the detectors in operation, versus the exposure time of the data taking campaign. The dashed region represents the range of statistical fluctuations due to the low number of counts expected, computed as the range encompassing the results of 200 different simulations. The red line is the average result. Also shown are the CAST 2003/04 limit (black dashed line), and the preliminary limits obtained from the 2013 (blue dashed line), while the region between the two dashed green lines represent the approximate sensitivity to be reached until the 25th of August 2014.
3.1.2 Solar chameleons

The expected flux of solar chameleons has been recently estimated as a function of several parameters, including the coupling to photons $\beta_\gamma$ and the direct coupling to matter $\beta_m$ (see arXiv:1409.3852, submitted to Physics Letters B). This in view of understanding the detection possibilities of the KWISP opto-mechanical sensor, described below, which is directly sensitive to the matter coupling $\beta_m$.

Figure 45 below shows $\beta_\gamma$ as a function of $\beta_m$ for decreasing values of the fraction of the total solar luminosity emitted as chameleons.

![Figure 45](image)

**Figure 45:** (taken from arXiv:1409.3852) - The graphs show plots of $\beta_\gamma$ as a function of $\beta_m$ for the case of chameleon production inside the solar tachocline and with the choice of $n = 1$ in the chameleon potential and of $\Lambda = 2.4 \cdot 10^{-3}$ eV for the energy scale (see arXiv: 1409.3852). The leftmost panel corresponds to chameleon production inside the tachocline only, with a solar magnetic field of $B = 30$ T for $R = 0.70 \ldots 0.75 R_{\odot}$. The rightmost panel corresponds to a magnetic field linearly decreasing from $B = 30$ T at $R = 0.7 R_{\odot}$ to $B = 1$ T at the solar surface. In both graphs the white areas correspond to a fraction of solar luminosity emitted as chameleons of $L_{\text{cham}}/L_{\odot} > 0.2$ (above), and $L_{\text{cham}}/L_{\odot} < 10^{-11}$ (below), respectively. The colored bands refer to values of the fraction between these two bounds.

With reference to the actual nano-membrane-based opto-mechanical force sensor developed in the INFN Trieste laboratory and to be installed at CAST (originally proposed by G. Cantatore and M. Karuza, see below), one can further estimate the fraction of solar chameleon flux reflected by the membrane, and the detection reach of the sensor with its present sensitivity.

Figure 46 shows plots of the fraction of the total chameleon flux reflected by the sensor membrane as a function of the direct coupling to matter. The two cases with and without a gold coating are considered.
under different incidence angles. Dashed lines in the plots refer to the level of sensitivity in flux fraction reachable with the sensor measured force sensitivity of a few fN in one s under two different measurement conditions, with and without the focusing action of the CAST X-Ray telescope.

The graph reported in Figure 47 below gives the projected sensitivity to Chameleon couplings to photons ($\beta_\gamma$) and to matter ($\beta_m$) when attempting the detection of a flux of solar chameleons using the KWISP sensor with the present force sensitivity of 50 fN in 1 second. The region covered by KWISP in the plot has been derived from the results reported in [1]. Two cases are presented in the figure. The grey-shaded region is achievable with the KWISP sensor tracking solar Chameleons for 1000 s without the help of the CAST MPE X-ray telescope. The larger color-shaded region is reachable after a 100 s tracking with the KWISP sensor mounted in the focal plane of the said X-ray telescope.

Projected measurement program for 2014-2015:

- sensor complete characterization in Trieste (end of 2014)

- preliminary off-beam commissioning: setup of sensor prototype in the CAST area and conduction of environmental and performance tests (end of 2014- beginning 2015)

- design of sensor coupling to the CAST beamline: choice between on-board or off-board laser source (see Figure 48) (2015)

- sensor assembly and on-beam commissioning (2015)

- live data taking
Figure 48: (Left) Schematic sketch of the "off-beam" setup of the KWISP force sensor with the laser source removed from the magnet; coupling to the sensor is achieved through an optical fiber. (Right) Sketch of the "on-beam" setup with the laser source mounted on-board the CAST magnet.


3.1.3 Relic particles

The possibility of turning CAST into an axion DM detector in a future phase of the experiment after 2015 could be strongly motivated under the light of the recent advances in the field, and has been under consideration by the collaboration since already some time see (CERN-SPSC-2013-022). Although more work is needed to configure a well defined program and proposal, something that will be done in the following year, we present here some preliminary considerations that could lead to a relevant DM search program in CAST. After the last advances in axion theory and cosmology, searches for DM axions in the mass range of about 0.01 to 10 meV are highly motivated. However, without a clear detection technique with proven sensitivity in this range, it remains totally unexplored so far. Recently, though, a number of new ideas are being proposed which need experimental validation. A potential DM program for CAST could include the realization of one or more test setups that could, at the least, serve as a technological demonstrator that could facilitate the extension to scaled-up setups in e.g. the future IAXO, without excluding that CAST could already reach sensitivity to a relevant fraction of the parameter space under some assumptions.

In the following we briefly review the motivation for relic Dark Matter axion searches and the state-of-the-art of the field, while later on we will present the three basic detection concepts under consideration for CAST: 1) the spherical dish antenna to perform wide-band DM axion detection (as suggested by D.H.H. Hoffmann, A. Lindner, K. Zioutas (see CERN-SPSC-2013-022)), 2) the concept of using dielectric-loaded resonant cavities to access "large" mass regions (around 10-3 eV) in relic axion detection (as suggested by Y.K. Semertzidis), and 3) the technology of long and thin cavities (waveguides) as suggested by I. Irastorza et al..

Axions as dark matter

The axion is a good candidate to compose the cold DM of the Universe. Non-relativistic axions can
be produced in the early universe by the phenomenon called vacuum-realignment (VR) and, in addition, by the decay of topological defects (TD) of the axion field like domain walls an axion strings (thermal production of axions is also possible, but it yields relativistic axions, i.e. hot DM). The computation of the relic axion density for a given axion model (and then to "predict" the needed axion mass to obtain the observed DM density) is plagued with uncertainties, both cosmological and computational.

In general, two main cosmological scenarios can be considered, depending on whether inflation happens after (pre-inflation scenario) or before (post-inflation scenario) the PQ phase transition. In the pre-inflation case only VR axions need be considered (TD are diluted away by inflation), but the computation depends on the unknown initial value of the axion field. In the post-inflation case, VR axion density is can be precisely computed but then TD axions potentially dominate and their computation is more uncertain. As a result, we remain with a fairly large range of masses where to search for the DM axion. Typically a mass range of about 0.001-10 meV is quoted as the preferred range, although much lower masses <0.001 meV are still possible in the fine-tuned models of the pre-inflation scenario, and values above 1 meV may also be possible in non-standard cosmologies or if only part of the DM is axions (a mixed WIMP-axion DM is viable and maybe even especially motivated).

Recently, the BICEP2 experiment announced the detection of primordial gravitational waves in the CMB. If true this would point to a very high energy scale for inflation. If PQ transition had happened before that scale, the axion field would have imprinted isocurvature perturbations in the CMB which are not observed. The BICEP2 observation and interpretation have been questioned and independent experimental confirmation is needed. If confirmed, the pre-inflation scenario for the axion DM would be ruled out, and the mass of the axion would be definitely constrained to values above ~0.01 meV.

Historical and technological reasons have focused the relevant experimental searches for DM axions to the mass range 0.001-0.01 meV. The ADMX experiment is the leader of such searches, and after many years of R&D it has demonstrated sensitivity to QCD axions in that mass range. Past runs have already excluded KSVZ axions in the 2-3 µeV slice (see Figure 49), and new runs are planned from next year on. If the axion is the dominant fraction of the DM and is in this mass range, ADMX will find it in the next decade. But, as seen, there is a strong motivation to extend these searches to higher mass values above 0.01 meV. A potential CAST-DM program may contribute to this goal, and in this way be complementary to the ADMX searches.

The conventional way to detect DM axions is based on Sikivie's haloscope concept [1]. It makes use of high-Q microwave cavities inside a magnetic field to transform the DM axions into photons. Being non relativistic, these axions convert into monochromatic photons of energy equal to the axion mass. For a cavity resonant frequency matching the axion mass, the conversion is substantially enhanced. The cavity must therefore be tunable and the data taking is performed by scanning very thin mass-slices of parameter space. The experimental implementation of this idea was pioneered in Brookhaven, and later on continued by the CARRACK and ADMX collaborations. As mentioned, ADMX has developed the haloscope technique to levels sufficient to detect axions in the few µeV scale. To apply the haloscope technique to higher axion masses is problematic for a number of reasons. First of all, given that the cavity must resonate at the axion mass, higher masses imply the use of smaller cavities, and therefore lower expected signals. Moreover, smaller cavities usually have poorer quality factors, and the noise figure of the microwave sensors usually
increase with frequency. New ideas are recently being put forward to overcome these problems and access the very motivated region above 0.01 eV.

Dish antenna

The Dish Antenna (DA) concept for the detection of relic ALPs has been put forward by D. Horns et al. in arXiv:1212.2970. The idea (see Figure 49 for a sketch) is to exploit the photonic part of the ALP wavefunction which, in the presence of an external magnetic field, can be absorbed and re-emitted by a conductor. If the conductor is spherically-shaped, the emitted "axionic" photons, expected to be in the RF energy band, are concentrated in the geometric center of the sphere, while normally reflected photons are concentrated in the optical focus, which sits in a different position. In addition, the DA, being non-resonant, is wideband, allowing access to the ALP mass region up to 10-2 eV which is extremely difficult to reach with standard resonant cavities.

![Dish Antenna](image)

**Figure 49:** Sketch of the dish antenna concept following arXiv:1212.2970.

In the case of CAST, one can give a preliminary estimate of the detection capabilities of a DA setup equipped with presently available RF-receiver technology. Figure 50 below shows the possible reach of a DA fitted inside the 43 mm CAST magnet bore equipped with RF receivers such as those used in the operation of the ALMA radio-frequency telescope (data courtesy of A. Lobanov, MPIfR Bonn). Three cases are presented:

- **CAST Dish**
  Magnetic field strength: 9T
  Diameter of the antenna: 43 cm
  Frequency range: 83 - 951 GHz
  Number of bands (receivers): 4
  Bandwidth of measurement: ~1 GHz
  Frequency resolution: 1 kHz (10^6 channels per bandwidth)
  Duration of single measurement: 1 day (measuring over the 1 GHz bandwidth)
  Effective scanning speed: ~1 GHz/day

- **CAST-Dish+** - Better signal processing: 100 Hz resolution

- **CAST-Dish++** - Cryogenic receivers: T

  noise varying between 4 and 10 K, instead of 40-200 K range)
The DA detector is also sensitive to hidden photon conversion to photons. Figure 51 presents a plot of the DA detection reach in the Kinetic-coupling vs. mass plane for hidden photons. The three detection conditions already considered for ALPs are shown.

![Graph showing detection reach in Kinetic-coupling vs. mass plane.]

**Figure 50:** *ALP detection prospects with a Dish Antenna at CAST (see text)*

The implementation of a DA-type relic detector at CAST, albeit its limited reach with presently available receivers, is captivating with its promise of entering uncharted territory in the axion parameter space, especially if detector technology can be pushed with the help of experts in the field. There is also the possibility that gravitational lensing effects on streaming axions or ALPs provide an essential enhancement factor bringing detection within reach.

The value of new detection concepts must be also considered under the light of CAST evolving into a precursor “multi-technique lab” still having a sizeable discovery potential and certainly paving the way for future efforts.
Dielectric loaded waveguide concept for relic ALP detection at CAST

For general concepts on relic ALPs detection with a waveguide see for instance O.K. Baker et al., PRD 85, 035018 (2012)

The probability of ALP to photon conversion inside a magnetic field is maximum when the external magnetic field is parallel to the electric field corresponding the photons coming from ALP conversion. One possibility to optimise this coupling when using a long dipole magnet, such as the CAST magnet, as the source of magnetic field is to use a rectangular waveguide to constrain the spatial modes of the electric field. In this case, since many modes are supported inside the waveguide, the length of the guide is limited to about 1.5 m due to nearby mode-crossing dissipating energy: this energy is not guided out of the structure and goes undetected, limiting sensitivity. Thus, the entire length of the dipole (9.26 m in the CAST magnet case) cannot be exploited unless multiple cavities are connected together with power combiners. This is technologically very challenging to do. The frequency range that can be explored with the waveguide concept appears to be a few GHz, corresponding to the 10-5 eV range in ALP mass. In the case of a long rectangular waveguide, the form factor, which measures coupling between external magnetic field and photon/axion field (maximum coupling being 1) is about 0.66.

Loaded dielectric resonator concept

Dielectric spacers in a waveguide (for example periodically spaced by some fraction of a wavelength, see also G. Rybka, Patras 2014 Workshop) can also enhance the coupling between the electric field and the external magnetic field (due to the fact that phase velocity in the dielectric changes with respect to free space, therefore modifying the field distribution). For example, periodically spaced dielectric elements of a given thickness may allow one to maximise coupling while avoiding mode crossing and overcoming length limitations. In addition, frequency tuning can be achieved by moving the dielectrics and changing the spacing.

Preliminary calculations show that a form factor of about 0.3 can be achieved. Tuning in the tens of

**Figure 51:** Hidden Photon detection prospects at CAST with a Dish Antenna (see text).
GHz range, corresponding to the 10-4 eV range in ALP mass, can also be obtained with form factors still above 0.1.

**Foreseen difficulties**

- understanding how critical are the tolerances on dielectric thicknesses and positions inside the waveguide
- finding a technical solution to the problem of tuning by moving the dielectric pattern inside the guide
- understanding how difficult it is to operate in cryogenic environment (1.8 K inside the CAST bore)

**Proposal for the CAST physics program**

Build a fixed frequency demonstrator, measure its properties, conduct a test run inside the CAST magnet. Work on toroidal (Tokamac-like) B-field and cavities prototypes is in progress in KAIST/ KOREA.

**Long thin cavities (waveguides) inside the CAST magnet bore**

The use of the haloscope technique with cavities shaped as long thin cavities (waveguides) was first studied in [2]. The idea is particularly well suited to the geometry of a dipole magnet like CAST’s. These cavities resonate at higher frequencies (in a long thin cavity the resonant frequency is mostly determined by the small sides of the parallelepiped) and they are particularly suited to match the mass range 0.01-0.1 eV. Despite the higher resonant frequency, the volume of the cavity may still be reasonably large, thanks to the length of the cavity, in part overcoming the drawbacks of the small cavities typically associated to high frequency. In addition, in case of a positive signal, one could get directionality information[3] (i.e. for some values of the axion mass and the length of the cavity, the output power depends on the orientation of the cavity with respect to the DM axion "wind") a very powerful handle to convince the community of the true origin of a DM signal, and a feature particularly well suited to the CAST magnet, which can be moved and oriented at will.

The experimental parameters affecting the expected sensitivity include the Q of the cavity, the total volume V of detection, the magnetic field B, the system noise, the integration time and some other parameters. By assuming reasonable values of the parameters very preliminary sensitivity projections for CAST have been calculated and shown on the right of Figure 52. The particular assumptions are explained in the caption. As shown, sensitivities by far improving CAST limit on axion-photon coupling for the mass range around 0.06 meV can be reached. The value of 0.06 meV is fixed by the cavity geometry (other values could be obtained with different waveguides width and height) and the mass width of the scanned region has been arbitrarily assumed 15% for this calculation. In reality it will depend on the tuning mechanism implemented in the cavity (and on the possibility of using several cavities with different dimensions). Indeed the tuning mechanism is probably the most important technical issue to be defined. Several ideas are under consideration, like the use of moving rods along the length of the waveguide, the use of moving walls, the use of a medium with tunable dielectric constant or the use of dielectric spacers carefully placed along the waveguide.

Pending this (and other) technical issues, which need to be carefully studied, the preliminary re-
results exemplified in the plot of Figure 52 are very promising. Such a setup in CAST could explore thin mass-slices of the axion parameter space in the range of maximum cosmological interest, and with a sensitivity well beyond the CAST helioscope limit, even approaching the QCD axion band at this mass values. The idea offers potential for scaling-up by power combining several of such cavities, if larger magnetic volumes are available like e.g. in IAXO. The combination of many such cavities should push the sensitivity and go into the QCD band at this mass values. The setup in CAST would then be a very important demonstrative first step towards a larger setup in IAXO.

The collaboration is starting the first steps to better define proposals in this direction. This includes to gather the needed know-how, to get involvement of additional expert groups, to define designs and feasibility tests (starting by testing some experimental parameters of a standard waveguide, see Figure 52), and to obtain the necessary resources from funding bodies.

3.2 Schedule for operation in 2014-2015

The present run with SRMM and new LLNL-XRT will continue until the 3rd October. Between 23rd September and 1 October, axion data taking has been stopped ~20-25 minutes before the end of each solar tracking to switch to sun filming mode (vertical refraction correction added).

The MPE-XRT will be reinstalled and aligned the week 6th-10th October followed by the Ingrid target alignment and then the installation of the InGrid detector and shielding. After commissioning for several days during which the SSMM will be reinstalled, data taking is planned to start around the 19th October leaving about 30 days data taking with the full complement of final detectors for the first time.

The schedule is summarized in Figure 53 below.

![Figure 53: Schedule of operations until the end of data taking in 2014](image)

The shutdown of CAST will effectively start on the 17th November 2014. The normal running period has been cut short by 3 weeks due to the CV intervention on the Cooling Towers of LHC8 (it cannot be put back later). On the 17th November, the magnet will be force-warmed up to ~120K before the cryo systems are stopped on the 21st November.

The winter shutdown of CAST 2014/2015 will contain the usual cryogenics and vacuum maintenance. It is also planned to make an upgrade to the primary pump shaft seals of the 1.8K Roots pumping group. This upgrade has already been successful made to the SM18 cryo system, however in SR8 it will entail the moving of the Roots pump several meters away from the corner to allow access for the crane. The cryogroup will make more in-depth maintenance on key cold valves in the system and implement new procedures for the transition from maintenance to operation and have agreed with CAST to the target date of the 1st April 2014 for the magnet stable at 1.8K. In view of the sun filming period being between 13-23 March, the cooldown may have to only start on the 23 March so as not to stress the cold feet of the magnet by tilting the magnet upwards whilst cooling down the magnet. There are no large-scale interventions planned for the shutdown except for a replacement of the chain clamps used on helicoflex seals on the general CAST vacuum system. In 2014, 3 chain clamps have failed in the MFB end of the system causing small leaks and necessitating rapid interventions.
For the detectors; normally all detectors will finish 2014 in final configuration and should not need interventions in the shutdown unless a further detector upgrade has been completed and is ready to install on CAST in time for data taking.

The present schedule for 2015 contains (see Figure 54):
- Normal Maintenance on CAST vacuum and gas systems
- Extended maintenance of the CAST cryogenics system
- Upgrade to Roots pumping group shaft seals
- Intervention to change all chain clamps on vacuum system at MFB & MRB ends.
- Sun filming (must organise magnet cooling around the 13-23 March so as to allow tilting.
- Cool down of magnet
- Magnet 1.8K (around start to mid-April)
- Quench tests
- GRID
- Start data taking
- After about 2-3 months data taking insert the KWISP detector in place of the InGrid for a first run to test KWISP sensitivity and take data on CAST. (Assume ~ 1month)
- Re-insert the InGrid
- X-ray finger runs with InGrid to check alignment
- Data taking for a further 3-4 months

In 2015 there should be ~ 6 month’s data taking possible with two XRT’s and InGrid and SRMM and SSMM.

**Figure 54: Present CAST schedule for 2015**
3.3 Requests for 2015

Estimates for the Cryo Operations (M&O) costs in kCHF, running hours, electricity power. Costs (cryogenics and power converter) and costs for the FSU contract for the power converter are shown in Figure 55.

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Figure 55: Magnet support costs, estimates for 2014 and 2015.

CAST requests from CERN continued support at a similar level to the past years, namely:

PH-DT: Consultant Mechanical engineer. Mechanical technician - support for the experimental apparatus including movement system. Electrical technician - support for Slow Control and interlocks and electrical support for SDD.

TE-VSC: Consultant vacuum physicist/technician.

Aid with the interventions on magnet and detector vacuum systems and in the X-ray lab.

TE-EPC: Support for the Power Converter (PC) operation and maintenance.

TE-CRG: Cryolab support for measures to place and maintain 3He system on Standby during vacuum running. Help with dismounting and re-mounting and all manipulation of cryo sensors. Support for the operation of the magnet cryogenics and its ABB* control system

Support for opening and closing the cryostat

TE-MPE: Support for the Quench Protection rack

EN-ICE: Support for the Power Converter controls system

BE-ABP: General Survey work and support for the alignment of two X-ray telescopes

EN-MME: Coordination of integration of detectors and telescopes on XRT platform

Studies for eventual integration of relic axion detectors in the cold bores
TE-CV: Support for demineralized water cooling system for 13 kA cables and Power Converter.

[*] It should be noted in addition to the cryogenics hardware, the cryo controls system (an ABB system over 20 years old) is now obsolete and has provided poor monitoring and archiving information to debug problems. ABB also have now enforced a best-effort contract on CERN with response time of 2 weeks compared with the assured 48hr response time up to the present. When the SM18 cryo controls upgrade is completed by the end of 2014; CAST will be the only major ABB system left in operation at CERN. CAST has received a strong recommendation from the Cryo Controls Group to make a changeover to a standardised modern PLC-based controls system. The cost is estimated at 250kCHF (Material + PJAS for 1 year) and a decision must be made by CAST & TE-CRG at the start of 2015 in order that the system will be ready for installation in the 1Q2016 in the 2015/2016 shutdown. TE-CRG has applied to the IEFC Committee in August 2014 for Consolidation funds for upgrades to a number of systems serving experiments including CAST. A decision is expected in October 2014

3.4 CAST Finances

2015 will be covered by a new 1-year Addendum (No7) to complete the solar axion program and in parallel take chameleon data with InGrid and KWISP.

4 Summary and outlook

1) Axion-like particles (2014-2015): In 2013 CAST has started again to take data with vacuum in the magnetic pipes. This type of measurements with better performing detectors have at least the potential to improve CAST’s own best record for the axion-to-photon coupling constant in the axion rest mass range below \( \sim 0.02\text{eV}/c^2 \). With the recently installed 2nd XRT, CAST has been upgraded as axion helioscope improving further its sensitivity to axion-like particles with rest mass \(<0.02\text{eV}\), utilizing for this purpose all 4 magnet exits. In case CAST observes no signal of axion-like particles, to beat the envisaged CAST limit by another experiment in this wide band rest mass range will be accordingly harder. In any case, such solar measurements have the potential to surpass the astrophysical limit, which has been recently reduced to the level of \( g_{a\gamma} \sim 6.6 \cdot 10^{-11} \text{GeV}^{-1} \) (see [1]).

2) Chameleons / Primakoff-effect (starting in 2014): With the commissioned InGRID detector, CAST can search, at least, in 2014-2015 again for solar chameleons at the one exit with the "old" XRT in front. Due to the very limited number of laboratory experiments searching for dark energy particle candidates, it is worth stressing that at the end of 2013 CAST became the first helioscope that has ever entered the dark energy sector. In fact, the data taken in the sub-keV range with an SDD last year are being evaluated at present, while preparing the first CAST publication on solar chameleons.

3) Chameleons / matter coupling (will start in 2015): Recent theoretical calculations for solar chameleons are quite encouraging for CAST aiming to search for such particles via their coupling to matter; the XRT can give rise to a signal enhancement by factor 100 to 1000 providing also a unique novel signal identification as the Sun moves across its field-of-view in about 80 seconds, for the stationary case. An interdisciplinary home built state-of-the-art force sensor has reached already the nominal sensitivity value in the laboratory in Trieste. To test its actual performance in CAST is the next critical milestone for this project, which should be clarified in 2015. In the ideal case, CAST with its XRT would have the potential to detect a very tiny solar chameleon luminosity (down to \( \sim 10^{-10} \text{L}_{\odot}\)).
comparison, the solar axion component CAST could have detected is at the $10^{-3}$ level. Interestingly, such a sensitivity in $\beta_{\text{matter}}$ allows to conclude also on the strength of $\beta_{\gamma}$, which no direct measurement by the Primakoff effect could reach. This is still true, even for a much smaller sensitivity level in $\beta_{\text{matter}}$ CAST should be able to achieve, hopefully, during the first phase of running with such a highly interdisciplinary detection approach. The reason for the relationship between $\beta_{\text{matter}}$ and $\beta_{\gamma}$ comes from the fact that chameleons are assumed to be produced by the Primakoff effect at the solar tachocline (at a depth of about 200000 km, and above). It is this fact which gives rise to this interesting relationship for the radiation pressure measurement, the signal strength of which depends on the flux of chameleons coming out of the inner Sun. Thus, CAST has a real potential to open a second window of opportunity in the dark energy sector, while aiming to search for particles like the theoretically introduced chameleons. CAST can be independently sensitive to the chameleon-photon and the chameleon-matter couplings, while the latter can link in addition both couplings. This will be a unique feature of CAST, once it starts this novel search for solar chameleons with the force sensor.

4) Relics /feasibility studies (starting in 2015): CAST is investigating since some time the possibility to be transformed to an antenna for relics, which should be the ultimate goal for a dark matter experiment. At present, even though the expected sensitivity for QCD axions is not reaching the theoretically motivated line, the collaboration thinks this is a worth doing first step as a realistic input for future scaled-up experiments in this field, e.g., for the proposed IAXO, and, for a toroidal Tokamak-like B-field configuration (Y.K. Semertzidis, prototype work in progress in KAIST/Korea).

In short, 15 years after the first presentation to the SPSC, CAST results remain a reference for this field of research. Moreover, the already installed and the planned upgrades of the experiment show that CAST, although being a relatively small experiment, still has a discovery potential for the whole research field of the dark sector: dark matter, dark energy, and the hidden sector. The contributions from new and also from external collaborators is worth noting.