Status Report of the CAST Experiment

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1. Introduction

In February 2009, CAST published the most restrictive limits on the axion coupling constant for masses that are -for the first time- in the range of the favourable theoretical region (JCAP02(2009)008). The publication was the result of the data taking run in the 2005-2006 period, when the magnet bores were filled with ^{4}He as buffer gas, which restores sensitivity for a narrow axion rest mass. This was the first part of the CAST Phase II. During this time, the experiment was sensitive to axion masses starting at 0.02 eV and increasing up to 0.39 eV by daily changes of the ^{4}He density (Figure 1).

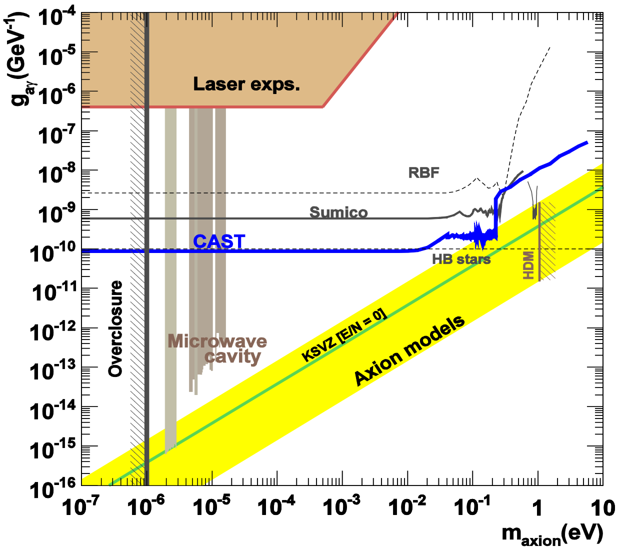

Figure 1. Exclusion limit (95% CL) from the CAST Phase I and ^{4}He Phase II data, compared with other experimental, theoretical and observational constraints.

In the preceding years (CAST Phase-I, 2003-2004), the experiment had searched for axions in the mass range up to 0.02 eV, when the magnet bores were kept under vacuum. The analysis of that data provided the best limit achieved by a helioscope over that mass range.

In 2007, the experiment moved to the second part of Phase-II, for which the system was thoroughly upgraded to use ^{3}He instead of ^{4}He inside the cold bore. The advantage the ^{3}He presents, is that it has a higher saturated vapour pressure at 1.8 K than ^{4}He (135 mbar c.f. 16.4 mbar) and so condenses at higher pressures, permitting CAST to insert higher densities inside the magnet bores and thus continue exploring the most interesting area in the axion phase-space, closing in the upper HDM (Hot Dark Matter) axion mass limit of 1 eV.

Data taking with ^{3}He started in 2008 and continues through 2009 to 2010. After a total of approximately 10 months of running, we are currently at pressure step #537 (50.56 mbar of ^{3}He at 1.8 K), equivalent to an axion mass of 0.75 eV.

In 2008, CAST expanded its searches for solar axions of low energy (a few eV). The hardware necessary for the low-energy studies will be permanently installed in the apparatus near the end of 2009 operations. This will allow simultaneous visible and X-ray measurements, with only minimal impact to the X-ray program.

In the following, a detailed account of the activities in the experiment and their present status is discussed in section 2. Comments on the current status of the data-analysis are given in section 3. The ^{3}He system performance is described in section 4 and that of the detectors in section 5, followed by comments on the low energy measurement setup (section 6). Details on the 2010 run estimates are given in section 7, before the conclusions.

2. Running in 2008 and 2009

a) Data-Taking in 2008 and 2009

The 2008 run

In 2008, CAST collected data in the period from 29.03.08 to 27.11.08 which contained a mandatory stoppage for the 8000hr cryogenics maintenance (40 days in September-October 2008). The density step size at the start of the run (setting #158) was still the standard dP setting (0.087mbar at 1.8K equivalent). On 07.07.08 the step size was increased up to 1.2dP after setting #276 until the end of the run. In all there were 201 calendar days available in 2008 and the number of new settings made was 252, or 126 tracking days with 2 step changes. This leads to an average data taking efficiency of **63%** over the year.

This data-taking ran relatively smoothly up until 10.09.08, the start of the cryo maintenance. The ^{3}He gas recovery in case of quenches was disabled during this first period as the pressures were relatively low. After the maintenance, the data taking efficiency dropped as CAST encountered a series of problems:

- The gate valve on the Sunset MM (VT1) developed a large 'transmission' leak and had to be disabled in 'closed' position (so preventing any further data taking in one of the sunset detectors).
- The cryo cooling for the magnet in the next weeks was unstable and had difficulty holding 1.8K with any magnet current and the window heating on until the problem of blocked oil filters at the output of the Roots pump was discovered.
- CAST operations were disturbed by two power cuts in SR8, 4 days apart, which were scheduled in order to optimize the LHC schedule.
- An air leak occurred in the experimental vacuum system at a metal joint on the outside of the cryostat. Air was cryo-pumped onto the cold pipe-work inside the cryostat near the cold windows. A week was required to carefully heat up this region to remove it.

Underlying the whole of the 2008 run was the presence of an undetected leak from the ^{3}He pipework into the isolation vacuum inside the magnet cryostat. At that time the only method at our disposal for detecting a leak to the magnet cryostat was through the measurement of the pressure in the cold bore, which due to the low pressures, the continuous stepping and the magnet temperature fluctuation remained under the detectable threshold. The leak was discovered on the 27.11.08 when setting #412 was repeated after the disruption of 2 weeks due to problems mentioned above. The difference was clearly visible in the 'cold bore' pressure P_{CB} (PT208 in Figure 10). P_{CB} is related to the total number of moles of ^{3}He gas present in the cold bore and the connecting pipe-work, but the value of P_{CB} varies with the relative temperatures of the cold bore and all the volumes connected to the cold bore.

At this point, CAST decided to end the data taking run and investigate the leak.

^{3}He leak

The ^{3}He leak was confirmed and measured by J-M Laurent of TE/VSC. It was estimated at $3.0\text{x}10^{-3}\text{mbar}\cdot\ell\cdot\text{s}^{-1}$ for about 30mbar pressure difference. After a series of tests to study the characteristics of the leak, the ^{3}He was recovered to the storage volume and the magnet was warmed up in preparation for an intervention in January 2009.

At the end of January 2009, the magnet reached room temperature and the cryostat was opened. A leak was found at the MFB end of the magnet, at a level of $1.0\text{x}10^{-3}\text{mbar}\cdot\ell\cdot\text{s}^{-1}$. A smaller leak ($5\text{x}10^{-5}\text{mbar}\cdot\ell\cdot\text{s}^{-1}$) was also found on a similar helicoflex metal joint at the MRB side. The findings (Figure 2) were that the leaks occurred on metal seals tightened by special strong chain clamps (type 300)[1]. These clamps have been used successfully on many cryogenic systems at CERN without major problems. The size of the measured leaks were consistent with the ^{3}He leaks observed at the end of 2008.

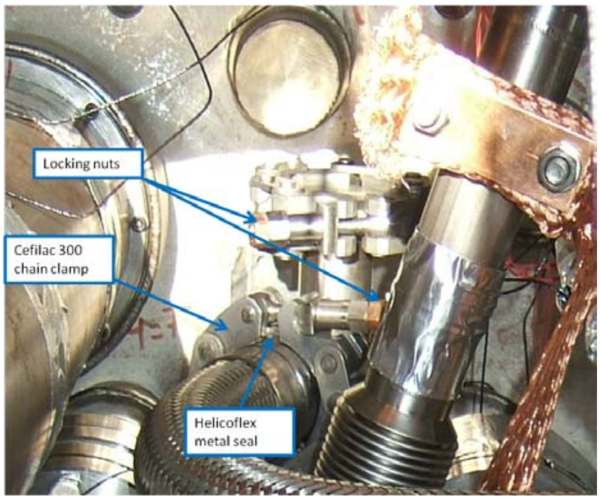

Figure 2. At the MRB end the chain clamp with locking nut after intervention.

The monitored data from the ^{3}He system in 2008 was analyzed in order to make a preliminary evaluation of the leak rate throughout 2008 and investigate the behaviour of the leak. In summary:

- A ^{3}He leak was present from the start of the 2008 run and was most likely created during the thermal cycle of the magnet over the Christmas 2007 shutdown.
- The leak rate increased steadily with increasing cold bore pressure.
- A further thermal cycle in September 2008 increased the leak rate for the same pressure difference by about a factor of two, reaching the final value of about $4x10^{-3}$mbar·ℓ·s^{-1} at 36 mbar in November 2008.

An inventory of the ^{3}He gas loaded into storage vessel in March 2008 and that remaining after recovering of the gas in November revealed a total loss of around 50ℓ (STP) ^{3}He from the initial charge of 450ℓ (STP).

The main consequences of the leak on the data taken in 2008 are the gaps (in axion rest mass) in the coverage. During 2008, the ^{3}He gas was recovered and refilled 4 times (quenches, bake-outs, cryo maintenance). On refilling to the nominal density of the last setting measured, a gap was created corresponding to the integrated gas leak loss since the previous filing of the cold bore. A more refined analysis using model-corrected values of P_{CB} has been made to recalculate the pressure/density settings affected. The gaps have been identified and the uncertainty on the edges of the gap has been estimated. Table 1 summarises these estimates. The gaps correspond to a backlog of 65 settings (including a reasonable overlap with existing settings taking account uncertainties). These gaps will be revisited and covered later.

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[1] Our conclusion was that the type 300 clamps were not tightened sufficiently during the ^{3}He system installation in mid-2007 (tightened to around 7N·m) even though they were leak tight at the time. Successive thermal cycles and vibrations had loosened the chain clamps sufficiently to be below the torque needed for assured leak-tightness. After consultation with the manufacturers and a number of experts in the cryo and vacuum groups, the ^{3}He team decided to change all metal joints and the chain clamps were tightened to 12N·m on the key joints (14N·m max limit) and 9N·m on less solicited joints and all chain clamp screws were locked with an extra locking nut.

In the scanning periods before each refilling of the cold bores, a further consequence of the leak is that for a given detector, successive density settings tend to be squeezed together, the extent of the squeezing depending on the time elapsed between the settings. For example, in the worst case of November 2008, the first setting of a sunrise tracking was nominally 1.0 step greater than the last setting of the previous day's sunrise tracking. Instead, due to the leak, it was actually only about 0.3 steps greater. Within a specific sunrise tracking of 1.5h, the second setting was about 0.02 steps closer to the first than had been planned.

Hence, over a long period of scanning the total mass/density range covered was less than expected. The compression of the settings however does enhance slightly the discovery potential and sensitivity of these points.

Table 1. Summary of pressure steps missing due to the ^{3}He leak.

Period	**1**	**2**	**3**	**4**	**5**	**6**
Date (2008)	26 April	27 May	30 June	3 Aug	9 Sep	13 Nov
Initial Step	157	188	224	269	325	374
Expected Final Step	187	223	268	324	374	412
Actual Final Step	181	216	257	313	362	392
Pressure Steps missing	6	7	11	11	11	19
Pressure gaps [mbar]	15.25 to 15.78	18.34 to 18.96	22.01 to 23.00	27.81 to 29.02	33.26 to 34.61	36.64 to 39.09

The 2008 Winter Shutdown

The original planning for the 2008-2009 winter shutdown had been to leave the cryostat closed to maximize the data-taking time in 2009. In view of the leak and the necessity to open the cryostat, the program was changed accordingly to accommodate this major intervention. Significant time was spent on the ^{3}He work which caused delays in the preparation of previously planned work. The main shutdown work was as follows:

- Upgrade the experimental and detector vacuum system and vacuum interlocks to allow operation with unheated cold windows (TE-VSC and PH-DT Controls).
- Add Cernox temperature sensors capable of operating accurately below 28 K in the cold window region (TE-CRG).
- Machine the magnet support girder to produce a wider gap between girder and foot of chariot during downward movements of the magnet.(PH-DT)
- Inspect 13kA power cables for aging and readjust suspension to relieve stress and added detection of water leaks at connection to MFB (PH-DT)
- Replace present cold windows with available spares. (Due to a problem, only 3 out of 4 were eventually replaced)(TE-VSC and PH-DT).
- Installation of a Residual Gas Analyser (RGA) to monitor for ^{3}He traces in the cryostat vacuum to complement the RGA monitoring for possible leaks through the cold window foils (TE-VSC).

The 2009 run

In 2009, the temperature profiles of the pipes connected to the magnet cold bores have changed significantly. This is due to the need to operate with the X-ray windows unheated, since as the gas density increases, the heat load on the cryogenic cooling at 1.8K increases up to an unacceptable level. In order to run with unheated windows, the experimental vacuum system and most detector vacuum systems had to be comprehensively upgraded involving 100 kCHF (including 500 h design effort). In addition, the temperature probes in the region between the cold windows and the magnet had to be upgraded to more accurately follow these lower temperatures (see more details in the ^{3}He section). The vacuum has seen nearly a fivefold improvement in the experimental vacuum and a tenfold improvement in the detector vacuum levels.

CAST started the 2009 data taking on 13.07.09 at the density setting #420 corresponding to 37.5 mbar at 1.8 K. Due to the ^{3}He leak in 2008, the remaining running time to the end of 2010 must now cover a larger pressure range than planned. Therefore, the pressure step of 1.2dP, used in the last part of 2008, has been increased to 1.4dP (dP is the nominal pressure step of the order of 0.1 mbar). The strategy for the ^{3}He data taking has been to cover two density settings per tracking. The main interruptions to the running period so far have been due to quenches. One of the four quenches (after the initial training quench) in 2009 was directly due to the activation of the LHC8 compensator/harmonic filter system. A protocol with TE-EL has been put into place to prevent any manipulations of this system without CAST first ramps down the magnet. This will not help in case of unforeseen trips of this system so in parallel TE-ECP are trying to develop protection circuits to make the magnet power converter less sensitive to perturbations of this type. At present, CAST has adopted the policy of ramping down the magnet during the day-time to reduce the risk of quenches caused by electrical and infrastructure disturbances during this period of intensive work on LHC. This policy has already averted at least one quench. In the period from 13.07 to 13.09, 103 density settings were covered, leading to a data-taking efficiency of **81.8%**.

b) Grid measurements

CAST performs periodically the so-called GRID measurements with the help of the team of surveyors at CERN. The measurements consist of an independent measurement of the position of the magnet in a set of reference coordinates (GRID), previously defined to cover reasonably all range of movements. They are intended to detect any drift in the pointing ability of the system with respect to the initial calibration values measured in 2002, which are used by the tracking software to determine the real absolute direction in which the magnet is pointing at any time.

The latest measurements were performed during May 2009. The system was found to be substantially unchanged (Figure 3) with respect to the September 2007 values, and in good agreement with the reference values of the grid of 2002, the ones used for tracking.

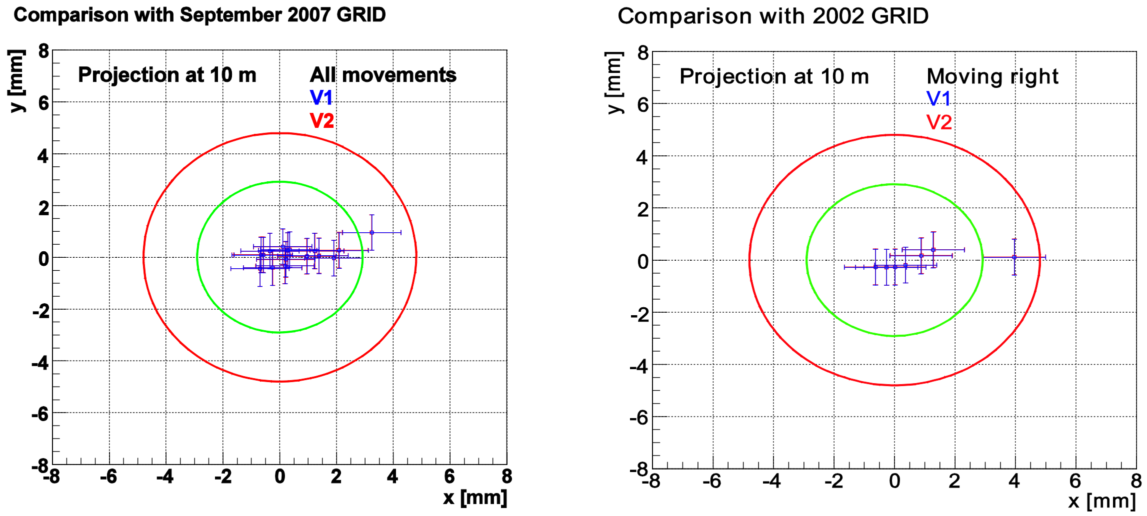


Figure 3. A comparison of May 2009 GRID with the September 2007 (left) and 2002 (right) situation. The required precision of 1 arcmin is indicated by the green circle, while the red one represents the 10% of the sun projected at 10 m.

c) Slow Control

The Slow Control System of the CAST Experiment is dedicated to monitor critical values of all variables concerning the stability of the experiment. The system is programmed to alert with messages in case of any suspicious change in an experimental value.

The system has been in operation since the beginning of the experiment's data taking (2003). An upgrade was necessary after all this time. A PCI-Express to PCI Box, like the one shown in Figure 4, has been implemented to cope with the increasing number of PCI cards necessary to properly monitor the system. In addition, the latest LabView version (8.5) was installed, resulting in both hardware and software modifications in order to adapt it to the new specifications.

Figure 4. New PCI Box Extension connected to the Slow Control PC.

d) The Sun/Galactic Filming

Twice a year, CAST has the possibility to test the tracking system by observing the sun through a window in the experimental hall. For this purpose, two cameras are aligned with the magnet axis and the "filming mode" of the tracking program is used to correct for effects of refraction for photons passing through the earth's atmosphere.

In fall 2008, the solar filming took place from 22.09.08 to 29.09.08.

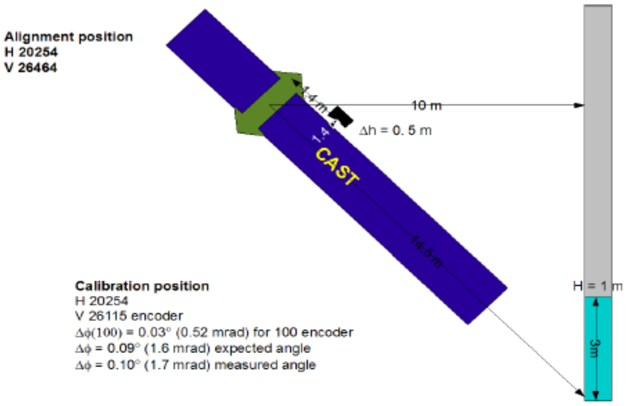


Figure 5. Setup of the Trieste system.

The same two filming systems as in spring 2008 were used in parallel. After their alignment by the surveyors on 22 September, reference pictures were taken shining a laser to the cameras. The different setups for the two systems are shown in Figure 5 and Figure 6, respectively.

After each filming run, the magnet was put back to the alignment position and pictures with the laser on were taken. In comparing the laser-checks of the two systems, it was possible to verify that they were aligned during the entire filming period. Due to bad weather conditions in fall 2008 the analysis of the pictures was challenging.

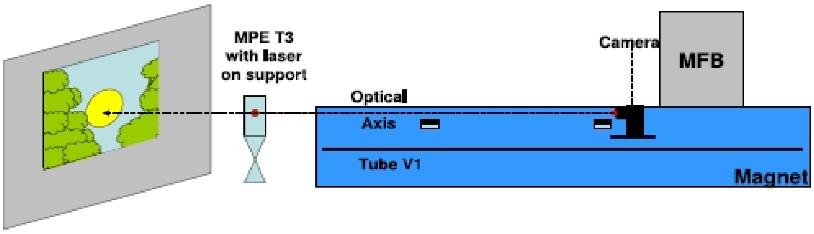


Figure 6. Setup of the Freiburg system.

It was ascertained that the magnet is slightly ahead in tracking as already earlier filmings indicated and it could be verified that CAST is pointing to the sun with the required precision of 0.02° (Figure 7).

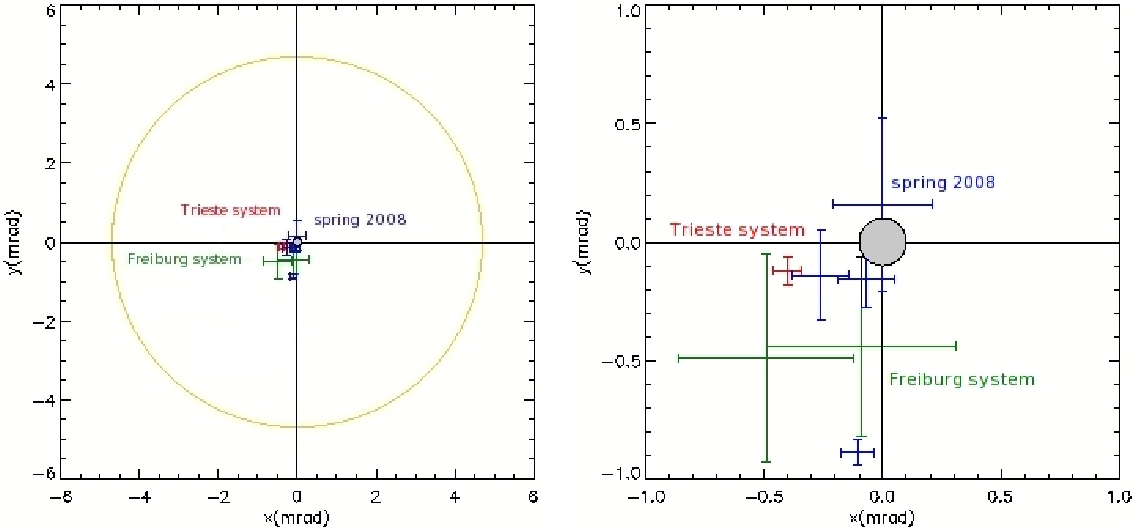


Figure 7. Results of the filming in fall (2008), compared to those of spring (2008).

Due to maintenance works it was not possible to move the magnet in spring 2009, so no sun filming was performed earlier this year. Some preliminary studies have been done with the aim to extend the filming period by moving the camera to the other side of the magnet.

Additionally, the first tests for galactic filming were performed in August 2009. The galactic filming uses the same principle as the sun filming. The only difference is that instead of tracking the sun, one tracks galactic objects like bright stars at night whilst observing them optically. This can be done with the Freiburg system. Hence it will be possible to determine the tracking accuracy when following galactic objects. That will be helpful for the analysis of the data obtained by tracking Sagittarius A*, Scorpio X-1 and the Crab pulsar during Phase I. Unfortunately, the environmental situation in the experimental hall makes it necessary to further improve the system before being able to image stars.

In fall 2009 the sun filming will take place in the period from 23.09.09 to 02.10.2009. By then, the system should be upgraded to be also able to perform galactic filming in the same period.

e) Cryoplant Status

The major 8000 h maintenance of the CAST cryogenics plant was made in September and October 2008. During the CAST shutdown in the beginning of 2009, some remaining maintenance tasks were performed and all the cryogenic systems were checked and no abnormalities were found. The cryogenic transfer lines to the magnet were all re-pumped to re-establish optimal vacuum isolation.

Since the re-start of the CAST cryogenics plant on 27.05.2009, the installation has run for 2266 h. All weekly checks indicate no abnormalities in the performance of either the compressor station or the cold box.

The Bauer recovery compressor, which constitutes part of the warm helium recovery system, has been overhauled and will be put back in service in September. This system, which is not crucial to the normal data taking mode of the CAST experiment, will be run in continuous mode for a week to determine its performance.

The current mode of operation of CAST (no window heating during data taking), has resulted in a significant reduction in helium through-put to the Leybold pumping group. Thus, there have been many fewer stops of the cryo system due to overloads of the pumping group.

The main source of interruptions to the cryogenic's operation remain perturbations to the electrical power system:

- 4 quenches have been attributed to electrical power supply problems,
- 1 slow discharge, due to a compressor stop, attributable to an electrical/water stoppage,
- 1 natural quench of the magnet,
- 1 pump-stop due to power supply problems,
- 1 pump-stop due to a software problem and
- 1 failure of a 24 Vdc power supply in the cryogenic control system.

Excluding failure of utilities, the CAST cryogenic system should remain in service until Christmas 2009, by which time the cryoplant should have accumulated approximately 4600 h, since April 2009 and 6500 h since the last major service.

3. Status of the overall analysis

The ^{3}He data acquired are currently being analyzed in order to define the corresponding exclusion plot on the axion parameter space. The statistical procedure followed was already used with the ^{4}He data and described in previous reports and in CAST published articles. No excess has been found so far, and therefore an upper limit on the axion-photon coupling can be obtained for the axion masses explored. The final exclusion plot can be defined only after the gas leak suffered last year has been precisely quantified, as this affects the precise gas density at a given time, and therefore the precise axion mass.

Nevertheless, given the detectors' backgrounds and exposures, the region of the parameter space which has been explored up to now with the ^{3}He data can be approximately indicated. At the moment of writing this report, the experiment has explored a region of axion masses up to about 0.75eV, as indicated in Figure 8 by a thick dashed red line, with a sensitivity of about 2 to 3×10^{-10} GeV^{-1} in axion-photon coupling values. A well-defined exclusion contour is expected by the end of the year for presentation in winter conferences.

As was already the case with the ^{4}He data, CAST is now sensitive to the QCD-favoured axion models for sub-eV rest masses. Using ^{3}He has allowed us to enter deeper into the yellow band of Figure 8, and every day the explored region grows. Perhaps more interestingly, CAST is for the first time sensitive to the KSVZ axion model (indicated with a green line) for specific mass values. This region is unexplored by previous experiments. Furthermore, it is compatible with astrophysical arguments, which exclude axion-photon couplings above $\sim 1\times10^{-10}\mathrm{GeV}^{-1}$, and with cosmological ones, which exclude axion masses above 1.05 eV. Hence, a discovery in CAST phase II is possible, with only minor discrepancies (of order a factor of 2) with limits derived from astrophysical observations of globular cluster.

Everyday a new, thin slice of untouched parameter space is being explored. Due to the sharp coherence effect, a clear positive signal in CAST may appear at tracking day.

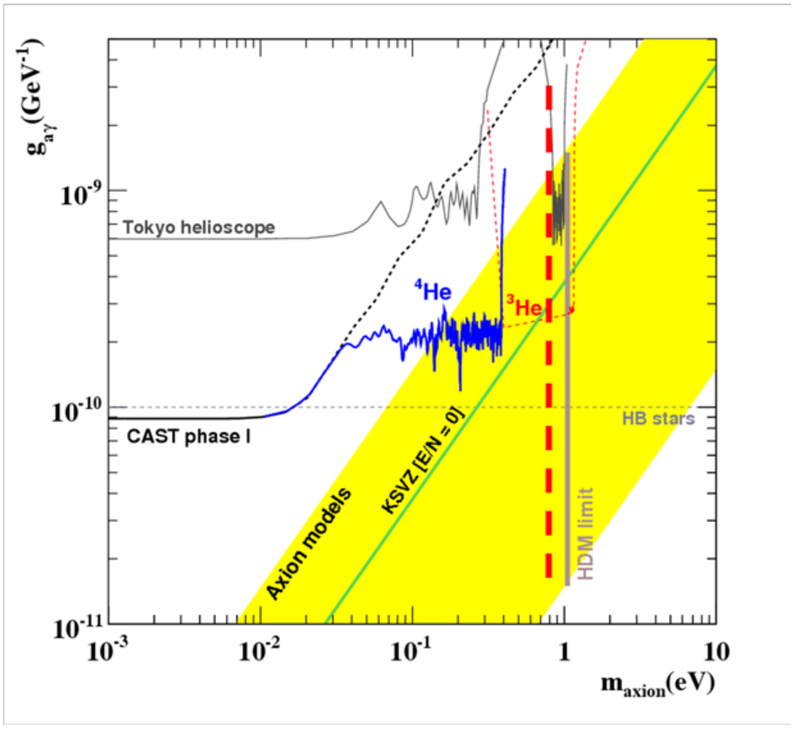


Figure 8. Exclusion limit (95% CL) from the CAST phase I and ^{4}He Phase II data. The thick dashed bar in red denotes the axion rest mass (0.77 eV) up to which CAST has scanned so far.

4. The ^{3}He System

The ^{3}He system has been in operation since April 2008. Up to now, approximately 380 pressure steps have been scanned and over 30 refilling operations and other significant manipulations were performed.

During the 2008 data taking, the protocol triggered at 5 occasions. In these cases, we returned to the previous pressure setting with a minimum and acceptable error of 0.000917 moles. That is the equivalent to ~3% of a step, thus confirming the accuracy and reproducibility of the gas transfer system, as can be seen in Table 2.

Table 2. Examples of Cold bore pressure reproducibility.

Date (2008)	Cause	Step N	Desired Moles	Actual moles before	Diff (n_{bef}-n_{des}) x10^{-5}	Actual moles after	Diff (n_{act}-n_{des}) x10^{-5}
29 Apr	Protocol	188	3.04749	3.05359	609	3.05376	627
01 Aug	Protocol	319	5.43871	5.43870	1.00	5.438694	1.6
03 Aug	Protocol	324	5.54348	5.543469	0.70	5.541753	170
26 Aug	Protocol	351	6.11173	6.111689	4.10	6.111696	3.4

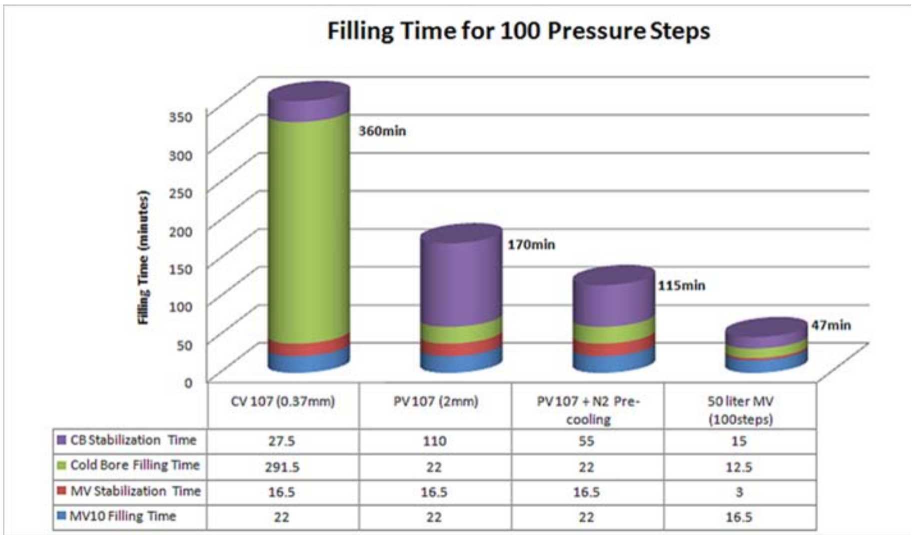
The shifters' user-interface has been constantly upgraded, minimizing the learning curve and risk of error by inexperienced shifters. Also, safety interlocks now assure proper response in case of a quench and provide a clear indication that the system position is correctly defined.

The plan (already in preparation) is to create an automated filling control scheme, where the shifters would only have to confirm if there will be a pressure change during the shift. The main obstacle is the communication between the Unicos Software with the LabView Quench program.

The main inefficiency of the gas system due to operational constraints was the very long and time consuming ^{3}He re-filling process after a quench or bake-out. This common procedure has become an important obstacle as we go up in pressure settings.

The first solution has been to install in parallel with CV107 (∅0.37 mm) an electro-pneumatic bellow sealed (on/off) valve with a bigger orifice, to take advantage of the maximum flow allowed by the needle valve (∅2 mm). With this upgrade, the normal 18 step filling cycle time of 59 min has been reduced to 26 min.

To further reduce this time, already under study is the installation of a pre-cooling nitrogen bath in the helium line, which would reduce the risk of thermal acoustic oscillations and diminish each filling cycle using MV10 (Metering Volume 10) by 10 min. At the present pressure setting this is equivalent to 5-6 hours filling time reduction.



	CV 107 (0.37mm)	PV107 (2mm)	PV107 + N2 Pre-cooling	50 liter MV (100steps)
🟪 CB Stabilization Time	27.5	110	55	15
🟩 Cold Bore Filling Time	291.5	22	22	12.5
🟥 MV Stabilization Time	16.5	16.5	16.5	3
🟦 MV10 Filling Time	22	22	22	16.5

Figure 9. Schematic representation of the time (in minutes) required to re-fill the magnet bores (MV = metering volume).

While this upgrade has reduced each filling cycle time approximately in half, there is still the noted systematic error with every filling cycle: For example, to reach 100 steps 5.5 filling cycles are necessary, while a new metering volume can reduce this to 1 filling cycle. It now takes 16 h to refill the cold bore, as the pressure rises, this time will rise significantly and reduce our overall data taking efficiency. To deal with this, the feasibility study of a new and larger 50ℓ metering volume is underway.

The upgrades are indicated in red in the flow-scheme of Figure 10.

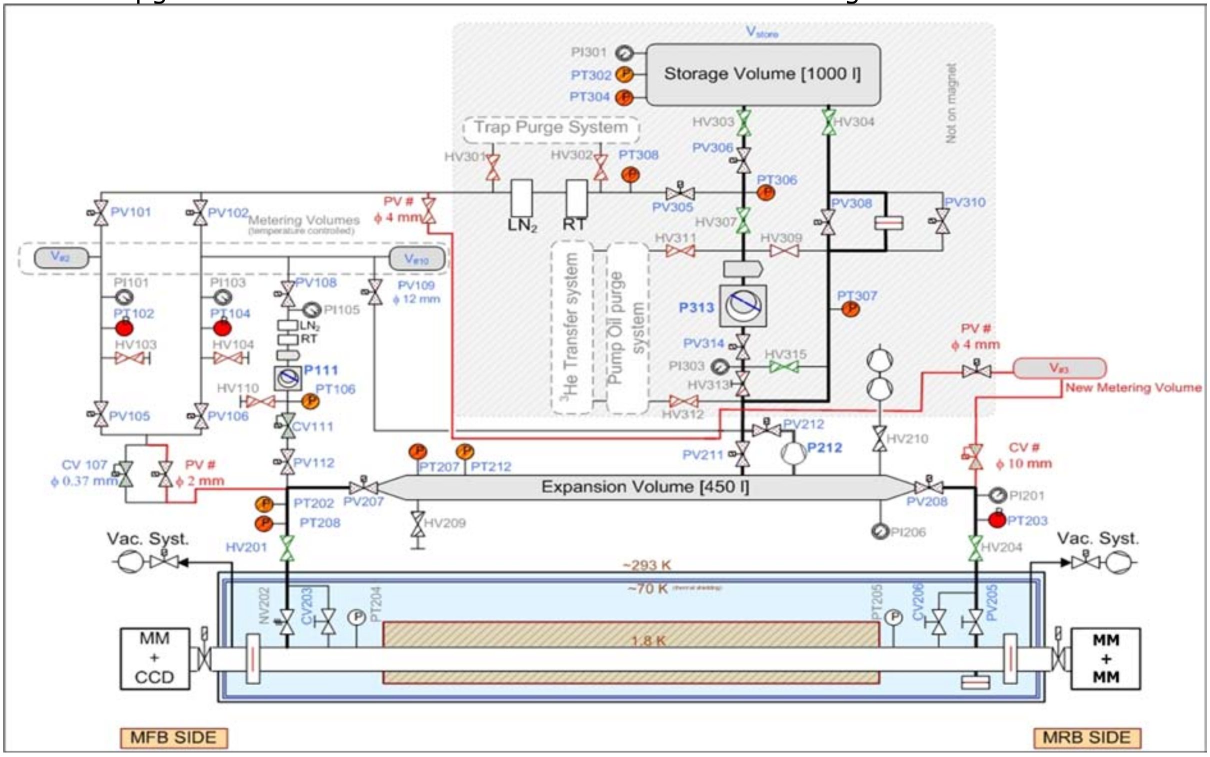


Figure 10. Flow-scheme with helium system upgrade.

The temperature probes used inside the cryostat (TVO) have been replaced by more sensitive, calibrated CERNOX sensors. All of the monitoring programs have been updated accordingly to include the new probes and other changes to the ^{3}He circuit. A new power supply for the bake-out of the windows has replaced the two old ones. The advantages it presents are the possibility to be operated remotely and that it provides data-logging.

In parallel, finite element calculations have been performed to estimate the thermal gradient of the X-ray windows during normal operation. Presently a computational fluid dynamic analysis of the ^{3}He convection currents during magnet movement is being performed (Figure 11). These calculations will give insight to the density and temperature variation that occurs throughout the cold-bore during altered working conditions, while they will also be used for the correction of the density records of the data collected in 2008.

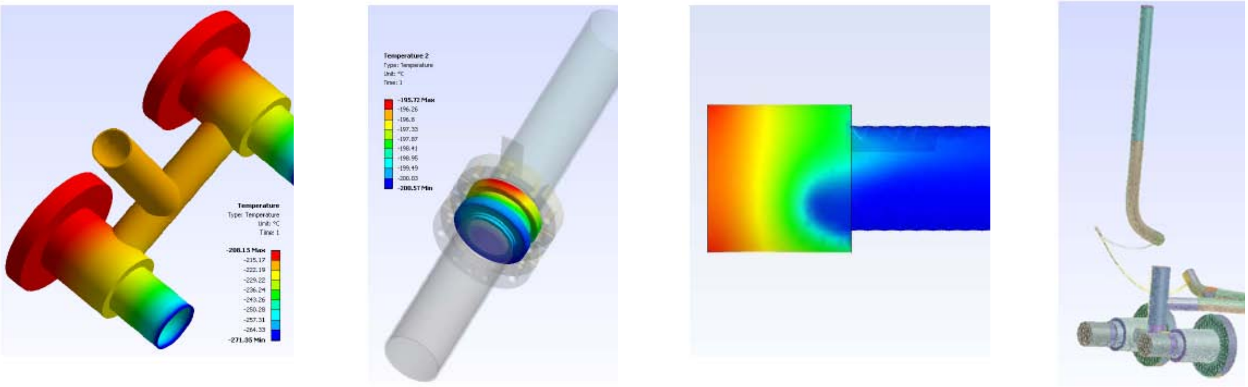


Figure 11. Finite element studies of the CAST X-ray windows & cold bore.

5. Detectors

a) The Telescope system

In 2008, the X-ray telescope with the new CCD was operating very stably and without any major problems.

With ^{3}He in the cold bore of the magnet, a total of 89.4 h of data under axion sensitive conditions (solar tracking data) and 1384.3 h of background data were acquired. These data in the energy range of 1 to 7 keV are shown in Figure 12. Two density steps were missed by the CCD detector but were covered by at least one of the Micromegas detectors.

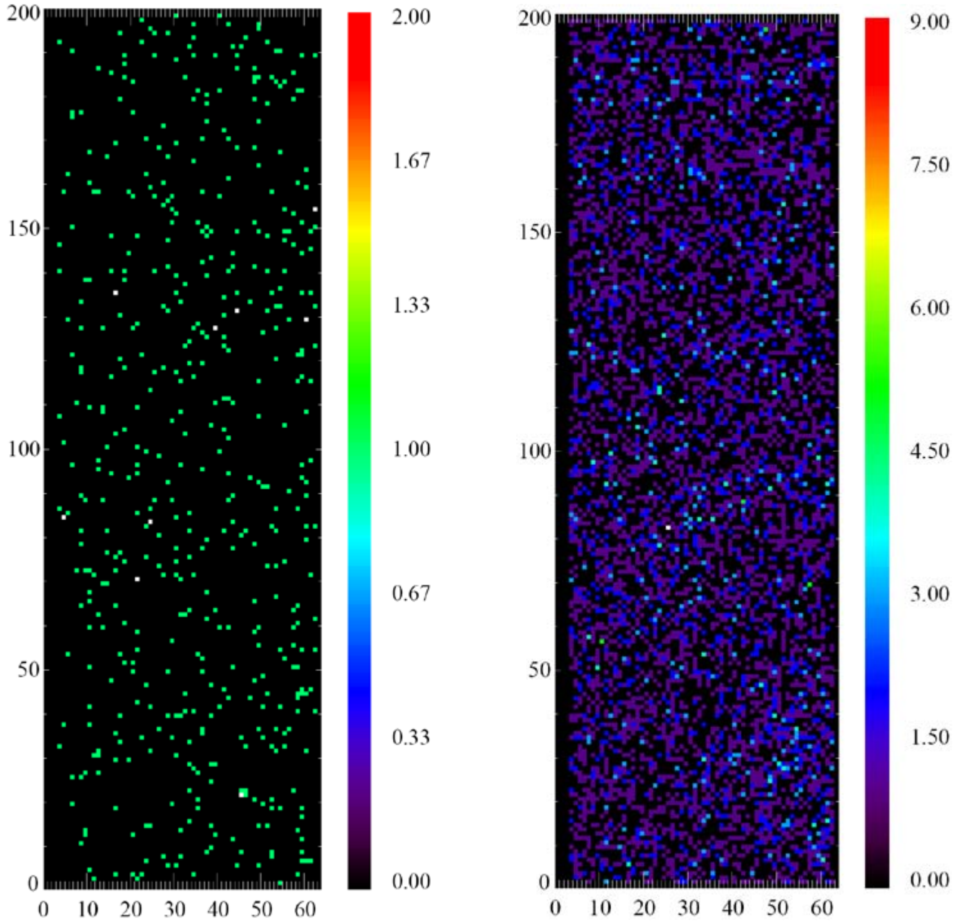


Figure 12. Spatial event distributions of solar tracking (left) and background (right) data acquired with the X-ray telescope in 2008 with 3He in the cold bore. The intensity is given in counts per pixel and has been integrated over the full exposure times, i.e. 89.4h of solar tracking and 1384.3h for background measurements.

The energy spectrum from 1 to 7 keV shows a homogeneous distribution and is consistent with the background spectrum of the formerly used CCD detector (see left image of Figure 13). The background count rate of the data acquired with the X-ray telescope is stable, as can be seen from the background light curve shown in the right part of Figure 13. This corresponds to a mean differential photon flux of $(8.87 \pm 0.08) \times 10^{-5}\,\mathrm{cts\,s^{-1}\,cm^{-2}\,keV^{-1}}$.

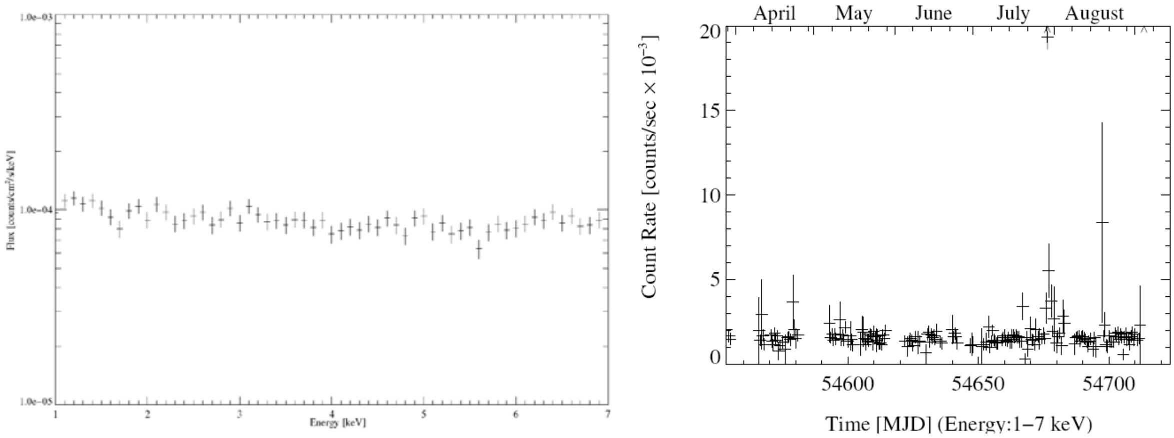


Figure 13. Left: Background spectrum in the energy range of 1 to 7 keV for the X-ray telescope during the data taking period with ^{3}He in 2008. **Right:** Background light curve observed with the X-ray telescope for the same time period in 2008. In the displayed energy range of 1 to 7 keV, the count rate is stable at a level of $(14.23 \pm 0.17) \times 10^{-4}$ cts s^{-1}.

2009 data taking

After the intervention of CAST in 2009 the X-ray telescope and its vacuum system were restarted and commissioned from the end of May until the end of June. After the alignment was finished, the X-ray telescope has acquired data in routine operation since beginning of July. The background differential photon flux has a mean value of approximately 8×10^{-5} cts s^{-1} cm^{-2} keV^{-1}, which is consistent with the previous results. The detector has a stable performance and provides high quality data, comparable to the level achieved in previous data taking periods.

A Frame-Store CCD Detector for CAST

In parallel to the data taking activities of CAST, the German consortium in CAST is preparing a backup detector system for the existing CAST pn-CCD detector. The new detector system will provide a higher sensitivity due to the expected lower background of the device and will be sensitive to photon energies down to 200 eV, an energy range which is of importance for the baseline program of CAST as well as for the low-energy axion program.

Although the present pn-CCD detector has already a remarkable low background, the system has several drawbacks: the detector was not built from selected radio-pure materials and the high Z-material close to the silicon chip results in fluorescent photons which contribute significantly to the observed background. The new detector system follows a state of the art design. We implemented a graded Z-shield (low Z material close to the CCD chip) to reduce the amount of fluorescent photon background in the energy range between 0.3 and 15 keV. In addition, all components close to the CCD chip are built from selected radio-pure materials.

The DAQ electronics, foreseen for the new detector system and are available in the laboratory in Darmstadt, can also be used as a backup system for the existing CCD detector. This provides additional redundancy in case of a failure of the existing DAQ system.

The mechanical design for the new system has been developed in close collaboration with the CERN engineering office. A schematic view of the new detector system is shown in Figure 14. We expect to make the first performance measurements in our laboratory in November and plan to implement the new frame-store CCD detector in CAST at the end of the winter shutdown of 2010.

Since the CCD chip has to be cooled to a temperature of about -40 to -80°C, we need a reliable and radio-pure cooling system for the new detector. Similar to the existing detector, we will use a Stirling cooler system with a cold head, which provides the required cooling power in combination with service free operation. For the thermal link between the cold finger and the detector we shall develop a new kind of heat-pipe which is built from high purity copper in collaboration with the Cryo-Lab at CERN. Such heat-pipes are not commercially available and require a significant amount of R&D, mainly due to the limitations given by the availability of radio-pure materials. The first prototypes of these heat-pipes have been successfully tested in the Cryolab at CERN during the past month.

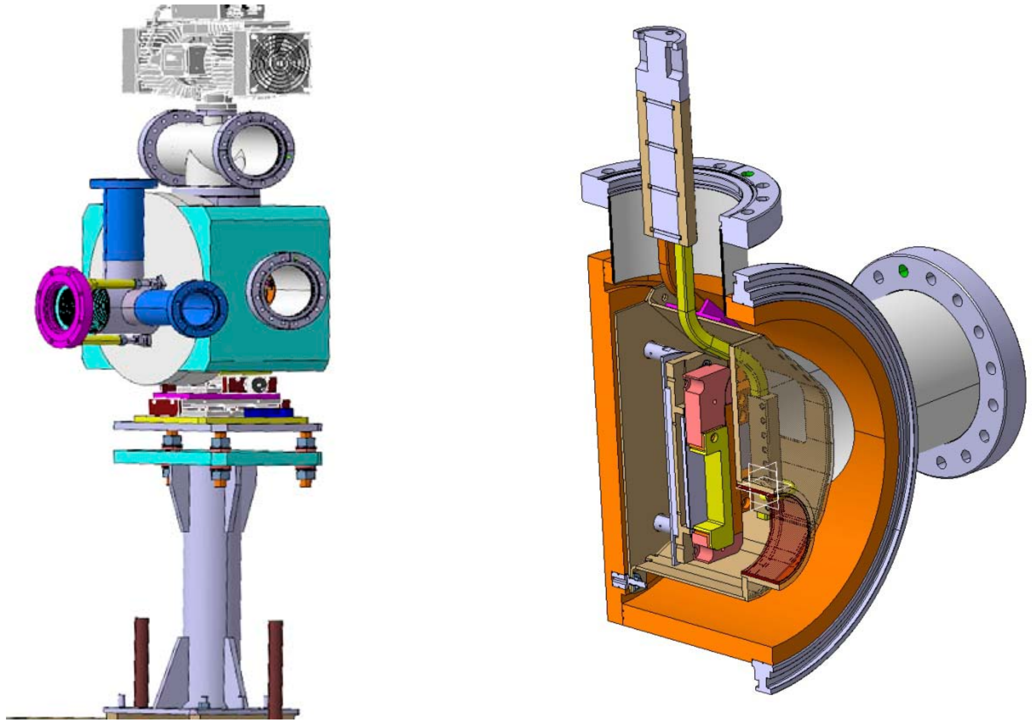


Figure 14. Schematic illustration of the new frame-store CCD detector for CAST. **Left:** (from top to bottom) Side view of the detector with the cooling system, detector vacuum vessel, x-y-z adjustment system and foot. **Right:** Schematic view of the internal detector components.

b) The MICROMEGAS detectors

Three microbulk detectors were ready for installation in CAST since September 2008. The microbulk technique has been developed the last three years. Now the process has been refined and in the last bunch of manufactured detectors the yield has been 100% with excellent performance. The CAST Microbulk detectors were the first 2-D detectors constructed with the Microbulk technique after considerable R&D for the complete mastering of the process.

The 2008 data taking: preliminary results.

The analysis of the 2008 data is still in progress. A summary of the preliminary results is given in Tables 3 and 4. For the Sunrise detector 245 pressure steps were covered during the data taking period, while for the Sunset Detector1 235 pressure steps were realized and for Detector2 at least 205. The remaining 30 pressure steps were lost due to a leak found in the gate valve to the cold bore in October. The analysis of the data is still in process and the number of steps covered might increase due to noisy data recovery.

Table 3. Preliminary performance of the Sunrise detector in 2008.

Sunrise Detector	Tracking Data	Background Data
Time [h]	206.85	5854.55
Counts	1097	36331
Mean Rate (2-7keV) [ctskeV^{-1}cm^{-2}s^{-1}]	$(1.27 \pm 0.06) \times 10^{-5}$	$(1.49 \pm 0.01) \times 10^{-5}$

Table 4. Preliminary performances of the Sunset detectors in 2008. A total of 205 pressure steps were covered for detector 1 and 205 pressure steps for detector 2.

Sunset		Tracking Data	Background Data
Detector 1	Time [h]	178.68	7070.04
	Counts	574	22586
	Mean Rate (2-7keV) [ctskeV^{-1}cm^{-2}s^{-1}]	$(1.23 \pm 0.05) \times 10^{-5}$	$(1.22 \pm 0.01) \times 10^{-5}$
Detector 2	Time [h]	146.00	5524.84
	Counts	437	16086
	Mean Rate (2-7keV) [ctskeV^{-1}cm^{-2}s^{-1}]	$(1.14 \pm 0.05) \times 10^{-5}$	$(1.11 \pm 0.01) \times 10^{-5}$

The 2009 data taking: a first look.

Sunrise Detector

A new vacuum line was installed in order to eliminate the amount of gas that might enter the magnet vacuum. The differential window was repositioned to minimize the "good vacuum" volume and the source manipulator has been placed in the "bad vacuum" side. The result was an improvement in the vicinity by a factor 10. The new line was also designed to allow the easy installation of a mirror-detector system for axion energies in the visible range, which will run in parallel with the X-ray detector without major interference.

A new microbulk micromegas detector was installed, using the same shielding. The detector design was identical to the previous one. The detector has shown a very stable behaviour as can be seen in Figure 15 and in Table 5.

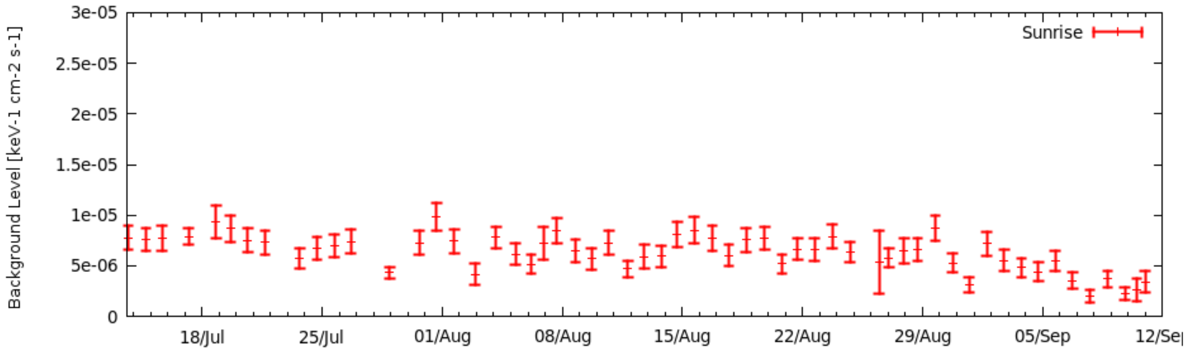


Figure 15. Background level as a function of date (2009 run).

Table 5. Preliminary performance of the Sunrise detector in 2009. A total of 97 pressure steps have been covered up to September 11.

Sunrise 2009	Tracking	Background
Time [h]	70.01	1580.44
Counts	87	2130
Mean Rate (2-7 keV) [cts keV^{-1} cm^{-2} s^{-1}]	$(4.75 \pm 0.5) \times 10^{-6}$	$(6.14 \pm 0.11) \times 10^{-6}$

The trend in the background level for the last 10 days is interestingly reaching very low levels of background (Figure 15). These ultra low levels of background were already observed in the past data taking. The origin of this downward trend is not completely explained, but could be partly compatible with Radon's decay time, which could be an indication that the observed background was affected by Radon radioactivity.

Background simulations as well as tests in the Canfranc Underground Laboratory are being performed in order to understand this effect fully (see last section).

The background spectrum is given in Figure 16. One can note the impressive low background at low energy (below 4 keV).

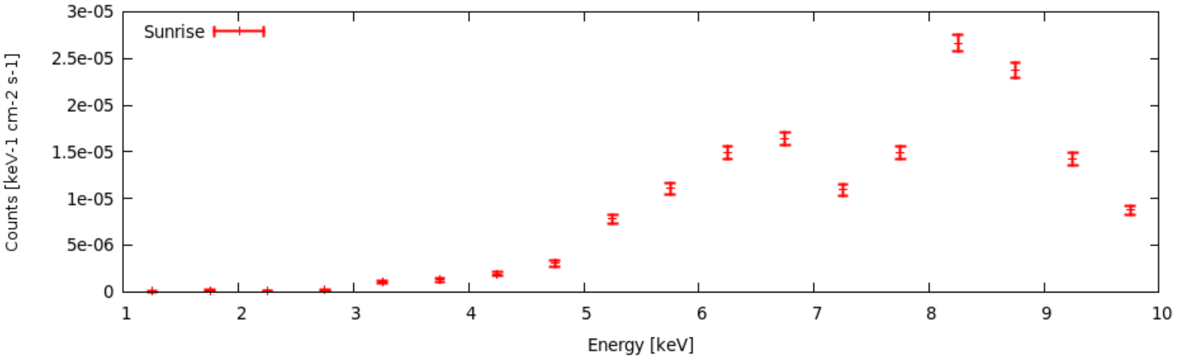


Figure 16. Background level as a function of energy for the 2009 data.

Sunset Detectors

The vacuum line was also redesigned in that side as well, to improve the general vacuum. The vacuum has been since then of the order of 10 times better than before. The preliminary performance is summarized in Figure 17 and Table 6.

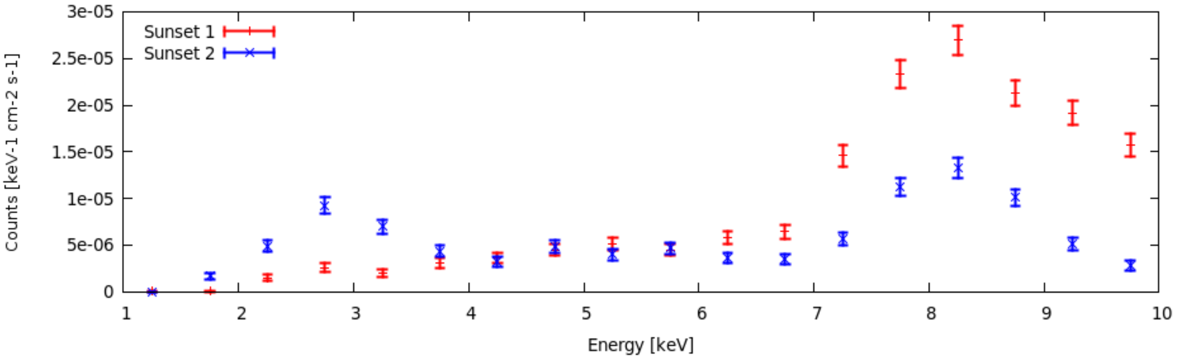


Figure 17. Background levels of the sunset detectors as a function of energy for the 2009 data.

The Sunset Detector1 covered at least 32 pressure steps, and the Sunset Detector2 covered at least 40 pressure steps. During this data taking period, the sunset detectors faced a period of electronic noise that complicates the data analysis. This is the reason why the number of steps listed above is a lower limit. The noise will be estimated in a more refined analysis.

Table 6. Preliminary performance of the Sunset detectors in 2009. Detector 1 has covered up to now 32 pressure steps and Detector 2 has covered 40 pressure steps.

Sunset 2009		**Tracking**	**Background**
Detector 1	Time [h]	21.85	533.65
	Counts	32	730
	Mean Rate (2-7keV) [cts keV^{-1}cm^{-2}s^{-1}]	$(5.60\pm0.99)\times10^{-6}$	$(5.23\pm0.19)\times10^{-6}$
Detector 2	Time [h]	27.70	728.35
	Counts	34	1384
	Mean Rate (2-7keV) [cts keV^{-1}cm^{-2}s^{-1}]	$(4.7\pm0.81)\times10^{-6}$	$(7.27\pm0.20)\times10^{-6}$

The apparent incompatibility between background and tracking data for the sunset detectors is known to be due to systematic effects related to pressure variations in the detector as can be seen in Figure 18. Moreover it is known that the relative position of the detectors in the experimental hall also has an effect. The final analysis should take into account pressure corrections as well as appropriate background definitions taking into account the position in the hall.

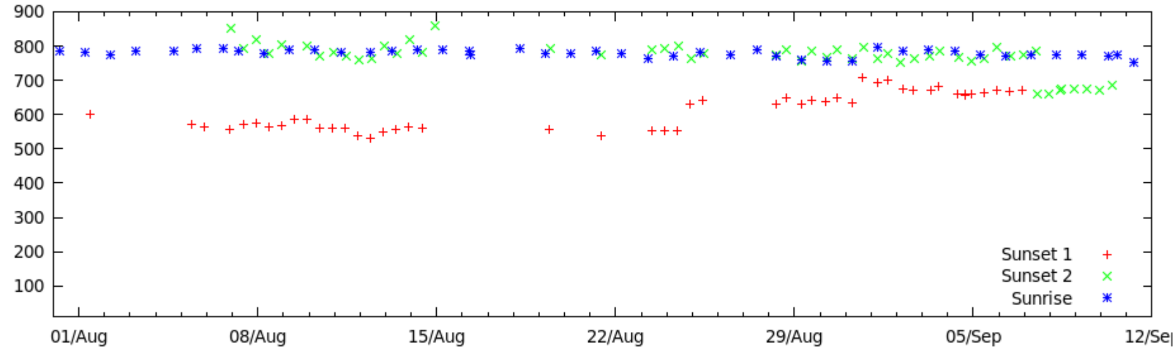


Figure 18. The gain history for all 3 micromegas detectors in the data-taking period of 2009.

Simulations and Background Measurements at the Canfranc Underground Laboratory

The micromegas team has undertaken a substantial effort to understand and quantify the very low background levels observed in the detectors installed in the CAST zone.

Geant4 simulations are being prepared with a detailed reconstruction of the shielding of the micromegas sunrise detector. These simulations will be executed in different configurations including information about radiopurity measurements that have been performed at the Underground Laboratory of Canfranc using the materials that compose the detector. The simulations are being developed implementing diffusion as well as the electronic readout that is actually working in CAST. The results obtained from these simulations will allow us to determine the relative reduction due to the actual shielding configuration and to study possibilities for optimization in the future.

The second area of study is focused on experimental background measurements in an environment with very well controlled parameters, such as nitrogen flow, radon abundance, etc. A new acquisition system has already been prepared in Zaragoza and the first measurements with a spare detector took place during the last months (Figure 19). A shielding and an automated calibration system is designed and is being built in order to finalize the system and place the detector in the Underground Laboratory of Canfranc.

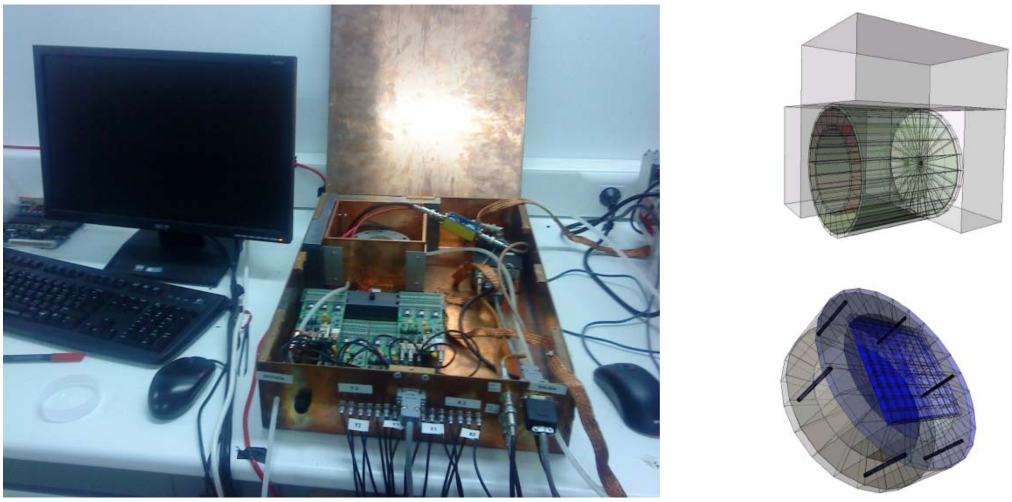


Figure 19. Left: CAST based acquisition system with a dedicated Faraday cage prepared for the low background measurement tests. Detector M13 is actually installed in the Faraday Cage. The copper cage is specially designed to fulfill a minimum leak rate to flush the detector with Nitrogen. **Right:** Parts of the micromegas simulation, shielding and detector.

6. Status of the setup for Low Energy Measurements

The setup for Low Energy Measurements at CAST is being upgraded following two approaches: improving the detector noise background and installing a permanent light collection system in one of the CAST beam lines.

The first step towards lowering the background of the BaRBE detector system is to study the performance of Geiger-mode Avalanche PhotoDiode sensors cooled to liquid Nitrogen (LN2) temperature by measuring the Dark Current Rate (DCR) and the efficiency. The sensors already tested in the Trieste INFN Laboratory are 50 μm diameter active area chips (mod. id101-50 made by idQuantique) with nominal 35% quantum efficiency at 550 nm. A series of chips of the same model and manufacture, but having different DCRs at 270 K, has been studied. Cooling tests were carried out on the higher DCR sensors and the background count rate at LN2 temperature, after correction for after-pulsing, was found to be lower by a factor 10^5 with respect to room temperature.

Figure 20 shows a graphical summary of the preliminary findings.

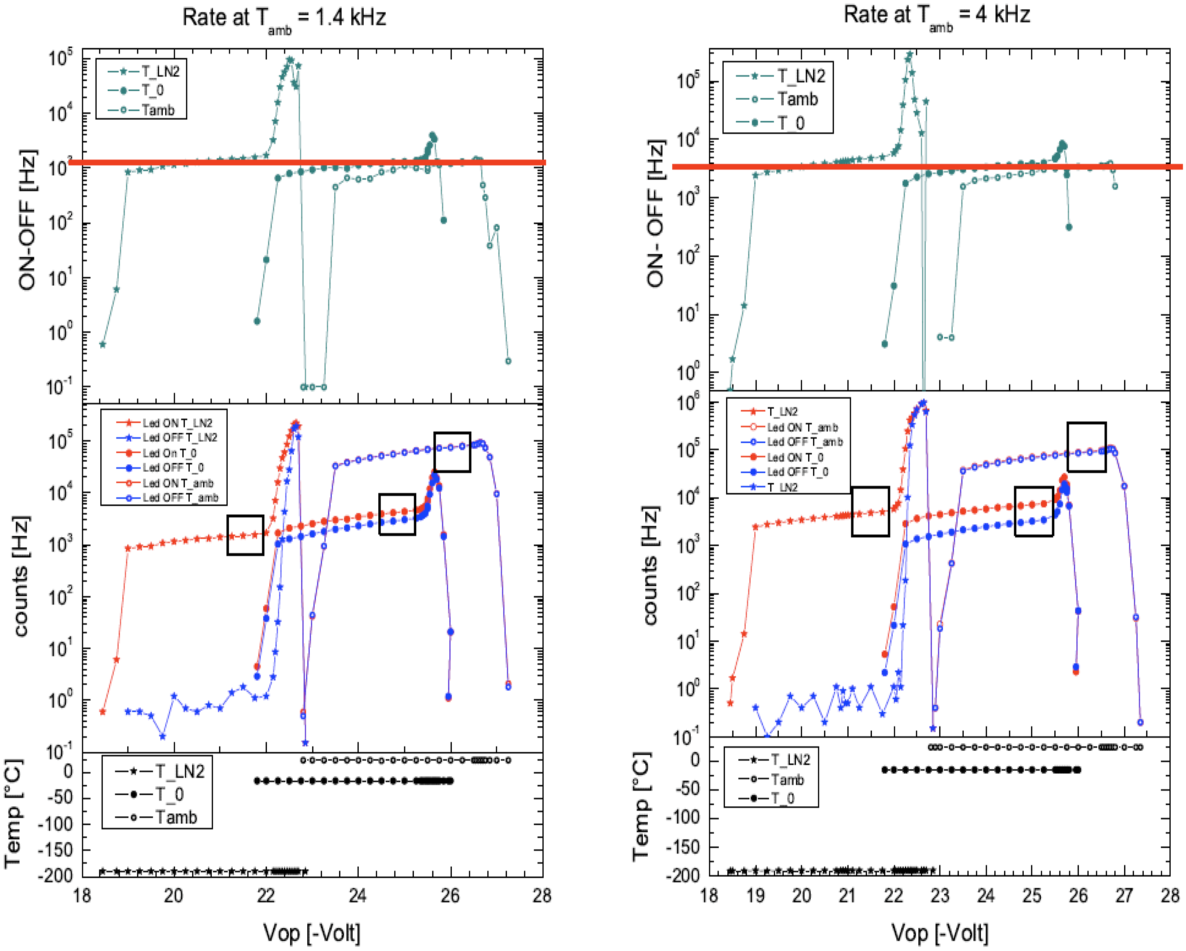


Figure 20: Characterization of a test G-APD detector at three different temperatures (liquid nitrogen, 0°C and room temperature) and at two different illumination rates, 1.4 kHz and 4 kHz, from a blue LED. The chosen working bias voltage regions are indicated by a rectangle. A reduction of a factor 10^5 in background is obtained when cooling the detector at LN2 temperature. The top graphs show a constant counting efficiency of the detector at the different temperatures, while the middle graphs show how the background drops by a large factor when at LN2 temperature (red points). Finally, the bottom graphs give detector temperature as a function of bias voltage.

To install a permanent optical coupling to the CAST magnet bore, a semitransparent mirror setup has been designed and constructed. It consists of a 1.5 μm thick Mylar foil, with 200 nm of aluminum metallization on both faces, mounted on an aluminum frame. This frame will be inserted in the beam at 45° to reflect low energy photons towards the input lens of a Galilean telescope. The telescope is then coupled to an optical fiber carrying light to the detector(s). Due to the negligible absorption of 4 keV X-rays by the mirror, this setup can be installed permanently in one of the CAST beam lines and run simultaneously during all data taking periods. Figure 21 shows photographs of the semitransparent mirror setup during bench tests.

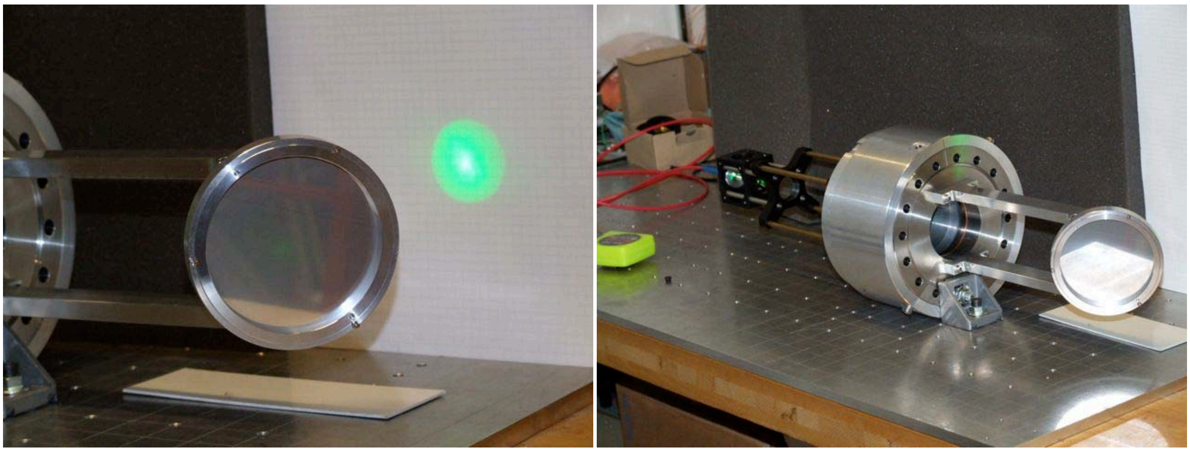


Figure 21. Left: Detail of the semitransparent mirror illuminated on the back surface by a laser beam propagating through the telescope. **Right:** General view of the semitransparent mirror setup.

7. Running in 2010

Plans for 2009 Winter Shutdown

The end of data collection in 2009 is foreseen for the 13 December 2009. The magnet will then be warmed up to 120 K and then left to warm passively over the Christmas 2009 shutdown. The cryogenics compressors will have accumulated ~6500 h. In week 2 of 2010, the cryogenic maintenance will begin and this should be over by the middle of week 6.

CAST does not plan to break the vacuum in the experimental vacuum or in the cryostat isolation vacuum. The leak tightness of the ^{3}He system will be carefully monitored during the thermal cycle.

The aims of the shutdown will be to:

- Complete dry-proofing of CAST cellar for storage
- Make small improvements to the upgraded vacuum systems where necessary
- Install further instrumentation on the ^{3}He system to increase the speed of refilling after a gas recovery
- Routine maintenance of pumps and magnet movement motors, jacks and frequency inverters
- Improvements to slow control environmental monitoring
- Installation of a visible detector system
- Improvements to shielding, electrical grounding/noise suppression on detector electronics.
- Possible installation of new FS-CCD
- Possible intervention on the 2 most worn magnet 13 kA cables (2 spare sheaths available)
- Survey GRID
- Sun Filming

The present estimate for the restart of data taking is towards the end of March 2010. This leaves at least 36 weeks possible for data taking or 250 days.

Data taking

A preliminary, conservative analysis of the ^{3}He leak indicates about 37 tracking days are needed in order to cover the missing gaps. Taking this analysis into account, CAST will reach ~103 mbar by the end of 2010 with the pressure step of 1.4 dP (dP corresponds to the FWHM of the resonance) and an assumed data-taking efficiency of 65 %. At this assumed efficiency, in order to reach 120 mbar, we will have to increase the pressure steps, likely to 1.75 dP.

The mass coverage for two consecutive settings is shown below for the actual pressure step of 1.4 dP in Figure 22. The impact of a bigger pressure step (1.75 dP) can be seen in Figure 23.

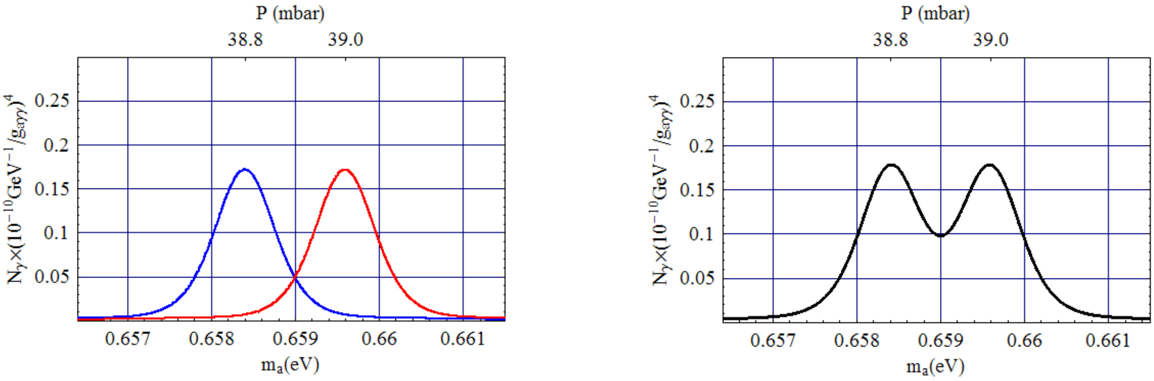


Figure 22. Left: Mass coverage for two adjacent settings for 1.4 dP. Right: Combined coverage of two settings.

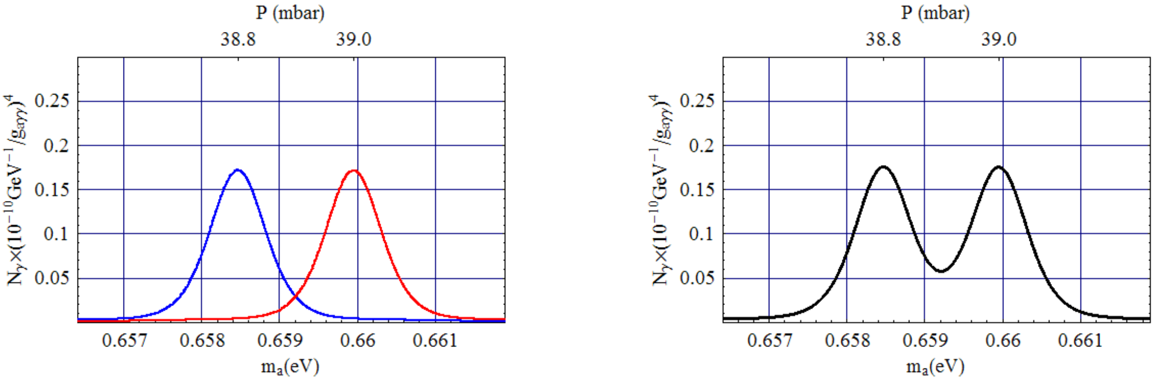


Figure 23. Left: Mass coverage for two adjacent settings for 1.75 dP. Right: Combined coverage of two settings.

Table 7 summarizes the estimates for the coverage until the end of 2010; this assumes a 65% data-taking efficiency over the period of 220 calendar days. We believe these numbers to be rather conservative. The pressure step size and running strategy will be re-evaluated in light of the actual efficiency and available running time.

Table 7. Two step-size scenarios and pressure ranges (with corresponding axion rest mass ranges) achievable in 2009 and 2010. The number of tracking days including a search protocol (65% of calendar days) is 100 and 106 in 2009 and 2010, respectively.

Step Size	**Pressure range covered**	
	2009	**2010**
1.40 dP	40.0-69.5 (0.67 – 0.88 eV/c^2)	69.5 – 102.8 (0.88 – 1.07 eV/c^2)
1.75 dP	40.0–77.1 (0.67 – 0.93 eV/c^2)	77.1 – 119.8 (0.93 – 1.16 eV/c^2)

By the end of 2009 we expect to have scanned the densities up to ~70 mbar, which adds up to ~520 pressure settings in total since the beginning of the ^{3}He Phase II (out of which ~370 will be taken during 2009). Assuming that we will continue running with the data taking efficiency of the last 2-3 months, we are confident that by the end of 2010 we will have reached the maximum density in ^{3}He of 120 mbar, covering the entire axion rest-mass range below 1.16 eV, the maximum value CAST can reach.

In parallel, the CAST collaboration follows actively the perspectives of CAST beyond 2010 for the short and the long term alike, following the potential use of new equipment addressing new physics.

Manpower and Finances

The running period of 2008 up to the start of the run in 2009 has been the most challenging for CAST in terms of manpower. This partially resulted from the successful completion of PhD programs by a whole generation of doctoral students. Their graduation meant that CAST lost a cadre of experienced shifters.

Our ^{3}He gas system expert was re-assigned to another CERN group in May 2008. Despite help from AT-ECR who shared a cryogenic engineer with CAST, the expertise and full time support was not re-established until spring 2009, when the part-time replacement became 100 % on CAST.

After this critical time in 2008, the situation is now much more satisfactory, partially due to the addition of three new PhD students. CAST very much appreciates the support of PH in allocating CAST a doctoral student (ultra-low background Micromegas) and an Applied Fellow (^{3}He Operation) in May 2009.

On the financial side, the CAST FRC held in February 2009 showed a potential deficit of about 130 kCHF projected to the end of 2010 (end of Addendum No3 to the CAST MOU). As a result, savings had to be made on mechanical support (FSU) and some items have been staged (in particular the new ^{3}He 50ℓ metering volume to speed up refilling after a gas recovery and SR8 infrastructure improvements). Applications are being made to funding agencies for exceptional funds and the Collaboration has responded generously and promptly with contributions for 2009 and also outstanding contributions from 2008 so averting any cash-flow problems. The present financial status is much improved and the projected deficit has been significantly reduced provided that the staged items remain staged.

CAST Magnet running Costs

The updated estimates for CAST magnet operations from 2008-2010 are shown in Table 8 below.

Table 8. Magnet support costs for 2008 & projections for 2009 and 2010.

Item	CAST/Dept	Units	2008	2009*	2010*
Cryogenics M&O (incl gases)	AT →TE	(kCHF)	180	170*	160*
Cryogenics power	TS→TE	*(hours)*	*7000*	*4872*	*7000*
		(kCHF)	193	134	180
Magnet Power Supply	TS→TE	*(hours)*	*3527*	*2730*	*5000*
		(kCHF)	25	20	36
PS Field Support	AB→TE	(kCHF)	5		
	CAST	(kCHF)		5	5
Annual Total	CERN	(kCHF)	403	323	376

** Estimates (New contract for Cryo-operations starting July 2009)*

8. Conclusion

CAST is the most sensitive axion helioscope ever built. Data taking during the ^{3}He part of CAST Phase II is proceeding smoothly.

Further upgrades are planned regarding the improvement of the ^{3}He system and the use of even lower-background and lower threshold detectors for the 2010 run.

With the given data-taking efficiency, CAST is confident that it will fulfil the original expectations of scanning the axion mass region up to ~1.16 eV, corresponding to ~120 mbar of ^{3}He inside the cold bores (at 1.8 K), with unprecedented sensitivity.