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Status Report of the CAST experiment and Request to run beyond 2007

The CAST Collaboration

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1. Introduction

The CAST experiment has been taking data successfully since 2003. During 2003 and 2004 the experiment was operating with vacuum inside the magnet bores (CAST phase I). The final results from the CAST phase I will be published in JCAP in April (hep-ex/0702006). The obtained limit on the axion-photon coupling constant is the best experimental limit over a broad range of axion masses and also supersedes the astrophysical limit from globular-cluster stars for axion rest masses up to 0.02 eV (see figure 1.).
In 2005, the experimental setup was upgraded to operate the second phase of the experiment. In order to extend CAST sensitivity to higher axion rest masses, the magnet bores have to be filled with a buffer gas (^{4}He at first and later on ^{3}He). The density of the gas has to be increased in appropriate steps to cover equally a possible range of axion masses above 0.02 eV.

CAST phase II run with ^{4}He started at the end of 2005 and was completed at the end of 2006. During that time, 160 density settings were measured. The highest density corresponds to 13.4 mbar at the cold bore temperature of 1.8 K (13.4 mbar @ 1.8 K).

The 2005-2006 data taking run has provided essential input for the design of the ^{3}He gas system, which has been conceived and dimensioned to operate up to near the physical limit of ^{3}He at 1.8 K (135 mbar). The installation of the gas system and cooldown will be completed by the end of the first half of 2007 and the commissioning tests and ^{3}He data taking will cover the second half of 2007.

Besides the scientific status of the CAST experiment, this report contains a request for extra running time. The CAST Collaboration is now confident that with steady and careful progress, operation will be possible up to at least 120 mbar @ 1.8 K. In order to fully exploit the axion mass reach of the system, we request a three year extension, running in 2008, 2009 and 2010.

CAST status report and the request for extra running time are presented in detail in the following sections: ^{4}He run in 2006 (section 2), prospects for ^{3}He run in 2007 (section 3), request for extra running time (section 4). Section 5 gathers the conclusions of the report.

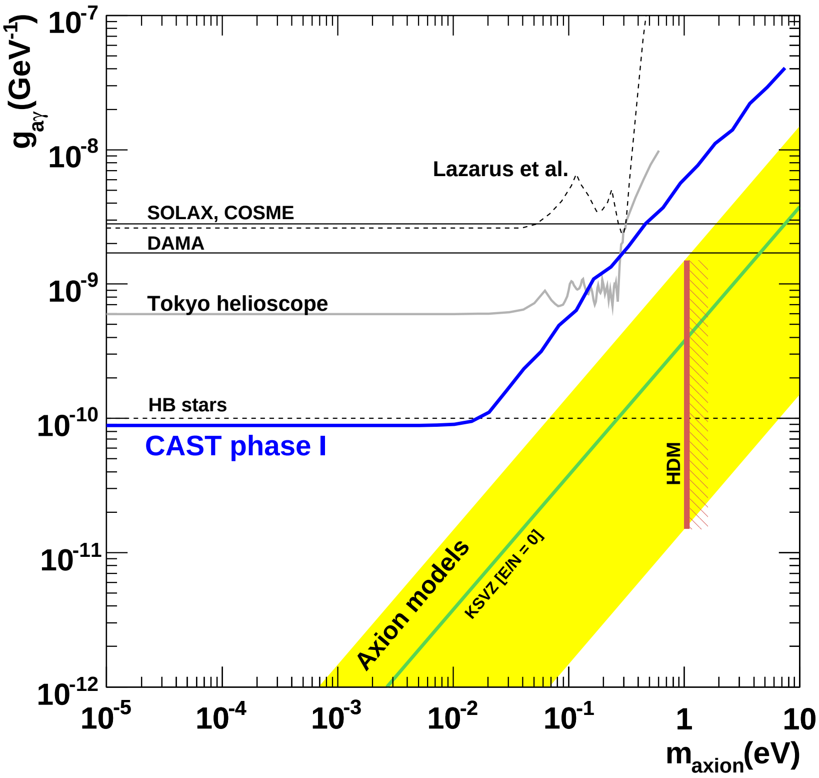

Figure 1: Exclusion limit (95% CL) from the CAST phase I data compared with other experimental and theoretical constraints.

2. Phase II ^{4}He run in 2006

CAST started phase II data taking with ^{4}He inside the magnet bores in November 2005. In 2006, CAST was taking data for a few weeks at the end of January and then continuously from April 29th until December 8th. The adopted scanning protocol was to increase the density of ^{4}He every day by an amount corresponding to 0.083 mbar @ 1.8 K. In this way, every detector was able to take data in each density step during one solar tracking. During the ^{4}He run, 160 density settings were measured covering the range of axion masses up to 0.39eV. Also, the Sun filming and GRID measurements were performed in October. In the following we give the results of the last grid measurements and solar filming, as well as the performances of the ^{4}He system and X-ray detectors during the ^{4}He run. The first preliminary results of the ^{4}He data analysis are presented.

2.1. GRID measurements

As it has been explained in past reports, CAST performs periodically the so-called GRID measurements with the help of the team of surveyors at CERN. These consist of independent measurements of the position of the magnet in a set of reference coordinates (GRID) previously defined to cover reasonably all range of movements. These measurements are intended to detect any drift in the pointing ability of the system with respect to the initial calibration values measured in 2002, the ones 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 April and October 2006. In April the system was found to be substantially *unchanged* with respect to the 2004 GRID, since only a small shift of 0.3 mm vertical and 0.4 mm horizontal was observed. However, there has always been a shift in comparison to the reference values of the grid of 2002, the ones used for tracking. This shift was of the order of ~1.3 mm in the vertical axis (due to the procedure of resetting the level value) and ~1.5 mm in the horizontal axis (due to the extra freedom that was introduced into the system in June 2003 because of the mechanical problems with the lifting screws). Although this shift was within our acceptance of 1 arcmin, we have been able to correct for it by readjusting the motor encoders. Furthermore we have implemented a new checking system based on laser sensors that allows us to immediately detect potential drifting of the order of few arcsec in both directions.

In conclusion, the tracking system has been performing well within our requirements during last year’s operation.

2.2. Solar filming

Twice a year, in March and September, it is possible to directly observe the Sun through a window in the experimental area and thus perform an optical crosscheck of the tracking system, the solar filming. For this purpose, a camera is aligned with the magnet axis and additional software is applied to consider refraction of photons in the atmosphere.

The solar filming had been repeatedly performed during the past. Thus for the 2003 and 2004 data taking phase it was confirmed that the magnet was pointing to the Sun while taking data with the accuracy required. Until March 2005, a webcam in combination with a small telescope was used to film the Sun. In order to improve the resolution and the alignment, the system was enhanced to provide a precision which matches the desired accuracy of the solar tracking (0.02°).Therefore, the new filming system consisted of an ST-7 CCD camera and better optics with 200 mm focal length. Furthermore, the concept used to align the filming setup with the optical axis of the magnet was changed. Thus a higher accuracy of the measurements and a better quality of the images was achieved. Already first tests in spring 2005 showed that the CAST magnet was pointing to the center of the Sun with an improved precision of the optical crosscheck, namely O(0.03°). A further enhanced setup was used in the fall of 2005. Not only was it made to be more rigid and thus damping vibrations but also to be more flexible and like this easier to align with the magnet axis. With this latest setup a precision of 0.02° was achieved at best and thus the accuracy of the tracking system could be reached. Within this precision, the magnet is pointing to the solar core from which most axions are expected to emerge. For March 2006 the analysis of the solar filming leads to a similar result with an even slightly improved accuracy of 0.015°: within the desired precision the CAST magnet is pointing to the center of the Sun.

In October 2006, only pictures with parts of the solar disk could be obtained due to bad weather conditions and trees preventing a full view of the Sun.

2.3. ^{4}He gas system

The objective of the ^{4}He gas system was to exploit the available range of the gas density, limited by the saturation pressure of 16.4 mbar @ 1.8 K (equivalent to the axion mass reach of 0.43 eV), whilst the final ^{3}He gas system was being developed.

Prior to the data taking period, a series of tests and additional research and development was done. The transient behavior of the rapid temperature and pressure rise during magnet quench was measured; the results served as starting point for the development of cold thin X-ray windows able to withstand a rapid pressurization while maintaining the required leak tightness to confine the gas in the cold volume.

Spontaneous thermo-acoustic oscillations were observed in the gas system, due to the steep thermal gradient in the gas column in the lines linking the cold bore tubes to room temperature parts of the gas system. These were eliminated by placing dampers in the areas where gas velocity is high according to the theoretical model of the phenomenon. Before this, the model was tested by verifying the frequency and the stability limits of the oscillations.

The operation with ^{4}He proved extremely useful for identifying the impact of the gas in the cold bore. The gas increases the convectional heat transfer between the cold bore tubes and the cold windows, which become the coldest point of the vacuum system between them and the detectors. To avoid that cryopumped gases accumulate onto the window film and cause a reduction of their X-ray transmission, the window flanges were heated to 120 K and the vacuum levels were improved. Moreover, the windows were regularly baked out at 180 K temperature. As the convectional heat transfer becomes still higher with the higher pressures accessible by ^{3}He, the windows cannot be operated at 120 K. The vacuum must therefore be improved by reducing the leaks from the detectors and by improving the pumping of the vacuum spaces.

The operation of the ^{4}He gas system was successfully accomplished by a daily step increase of the gas density in the magnet cold bores, made by trained shift crew following an established protocol.

2.4. pn-CCD and X-ray telescope operation

The pn-CCD detector and the X-ray telescope were operated during the 2005/2006 data taking period with ^{4}He inside the cold bores, in the same configuration as during the 2004 data taking phase. The data analysis of phase II yields ~300 h of useful data during axion sensitive conditions and ~2740 h of background data. The resulting intensity images for the full background and tracking data are shown in figure 2. Both images for the full data show a homogeneous distribution over the full CCD chip. The time averaged background and tracking spectra for the phase II data are shown in figure 3.

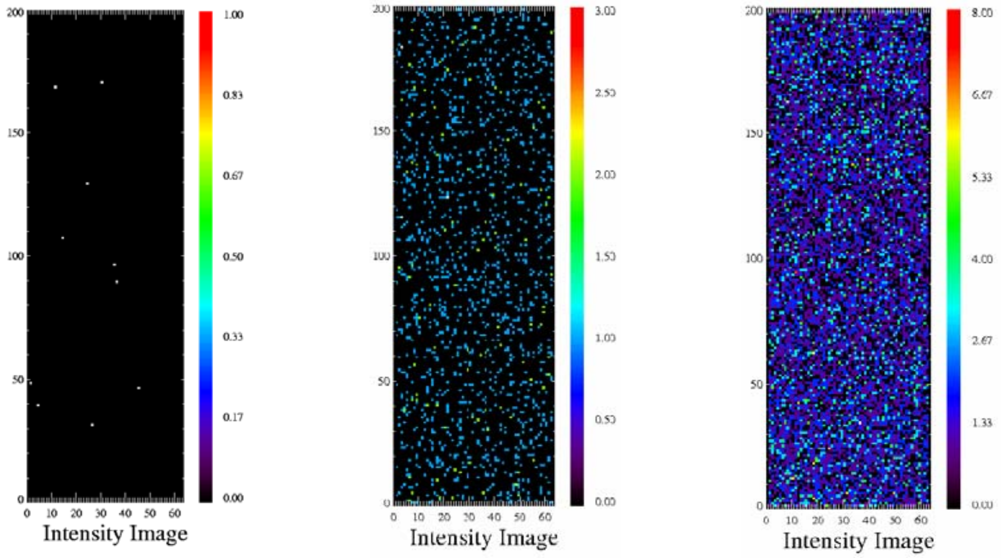

Figure 2: Intensity distributions for the energy range 1-7 keV. Left panel: Intensity distribution for 1 single solar tracking with an average exposure time of 5707 seconds. Middle panel: Homogeneous intensity distribution of the solar tracking data of the entire data taking period (exposure time ~300h). Right panel: Homogeneous intensity distribution of background data of the entire data taking period (exposure time ~2740h).

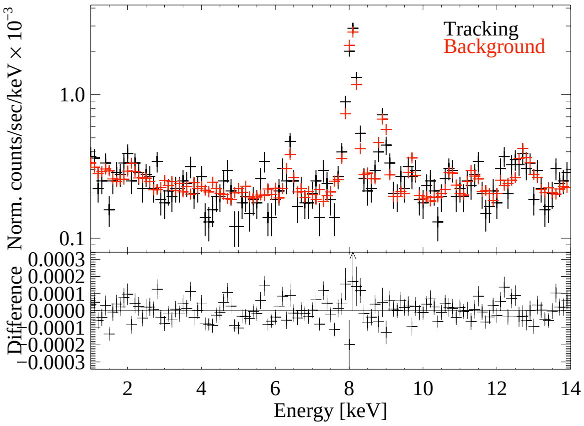

Figure 3: Normalized spectra acquired during the entire solar tracking and background exposure times in the energy range 1-14 keV. In the lower panel the difference between the two spectra is shown.

In phase II, 189 solar trackings and 144 density-steps out of 160 density-steps in total were completed. The 16 missed density-steps were nevertheless covered by the TPC and MM detectors and these settings for the CCD can be repeated in 2007 during the commissioning period of the new gas system, since the magnet bores will be first filled with ^{4}He. Both, the detector performance and the mean differential photon flux were stable at a level of $8.54 \pm 0.17 \times 10^{-5}$ counts/cm^2/s/keV, which translates to a count rate to 8.08 ± 0.21 counts per tracking run on the full CCD chip in the energy range 1-7 keV. The X-ray telescope can produce an "axion image" of the Sun by focusing the photons from the magnet bore area to a ≈ 6 mm^2 spot on the CCD. This results in an expected count rate of 0.24 ± 0.04 counts per tracking in the signal spot.

During an intervention in October 2006, the vacuum system of the CCD detector and the X-ray telescope have been extended and upgraded. As a result of this, the vacuum in the detector system could be improved and pumping of the whole assembly has been facilitated. The control software has also been updated to a more safe and more flexible system, which includes, among others, interlocks to and from the magnet vacuum, remote access option and a more structured user interface. Regular measurements with an X-ray source were made during, before, and after the data taking period to verify the stability of the alignment of the X-ray telescope, based on reference measurements made in 2004. These measurements have verified the stability of the spot position on the CCD chip.

Due to the use of cold windows in phase II, the effective area for the X-ray telescope system needed to be recalculated taking into account the geometric and absorption losses due to the strongback of the window. The geometric transmission of the strongback was estimated to 87.4% based on X-ray transmission measurements at the PANTER test facility in Munich. The resulting effective area is shown in figure 4 together with the effective area without cold windows.

The preliminary result of the data analysis of phase II is shown in figure 5 and it demonstrates that in phase II we have entered the region favored by theoretical axion models.

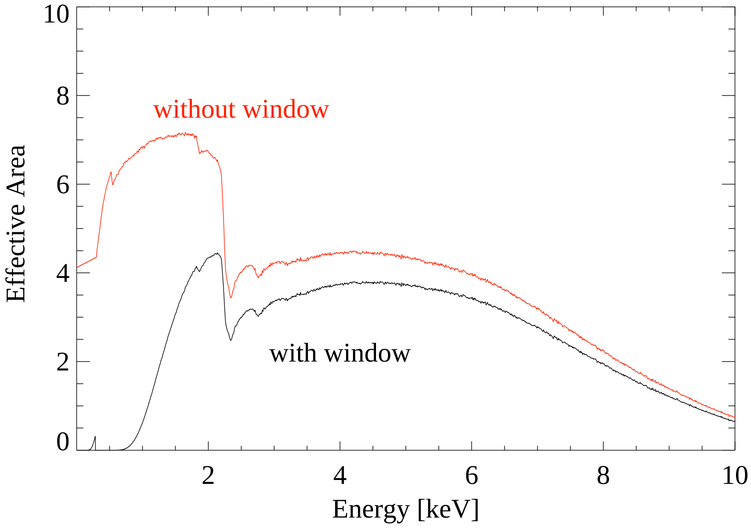

Figure 4: Effective area in cm^2 for the X-ray telescope system for phase I (without cold window) and phase II (with cold window). The transmission of the windows 15µm thick PP foil and the loss due to the strongback (estimated to 12.6%) are included.

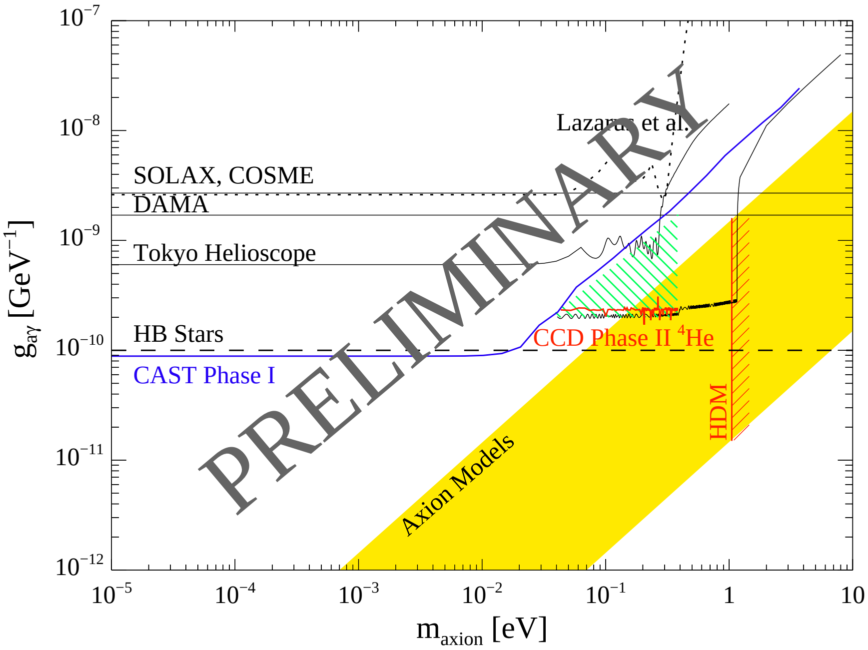

Figure 5: Preliminary upper limit (95% CL) of the axion-photon coupling constant $g_{a\gamma}$ depending on the axion mass m_{axion} for the X-ray telescope system, derived from the CCD data of phase II with ^{4}He inside the cold bores (red line). The black line shows what is expected for CAST phase II data taking. The green shaded area shows the region that was already scanned during the data taking in 2005/2006. The results of earlier experiments are shown as well.

2.5. Micromegas operation

For the second phase of CAST (2005-2007) the detector was dismounted during the winter shutdown and at the end of April 2006, during installation, an incident required the replacement of the detector. The design of this new detector was identical to the one used for the first runs except for an improved feature: the amplification copper mesh was coated with gold with the purpose of stopping the 8 keV photons originating from copper fluorescence that dominated the background. This improvement was expected to lead to a reduction of the background level around 8 keV. This reduction of background is visible in figure 6 where the background spectrum is shown before and after the intervention.

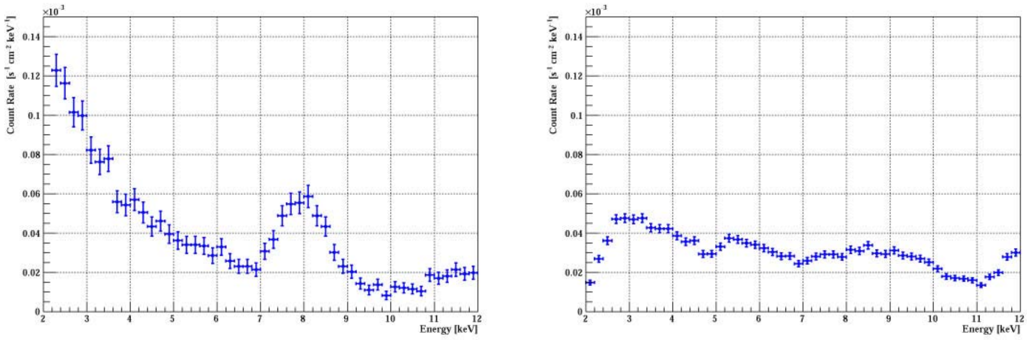

Figure 6: On the left, background spectra for the 2005 data taking. On the right, background spectrum for the 2006 data taking after having replaced the detector with a coated gold mesh. The background around 8 keV has been reduced by a factor 2.

The detector ran smoothly and in a stable manner accumulating 145 data sets in 160 pressure steps up to 13.42 mb, representing 3306 hours of background and 277 hours of tracking. The detector stability, estimated by the evolution of the risetime of the mesh signal for a period of about 6 months is within less than 2%.

A preliminary analysis of the data results in a limit of the axion-photon coupling constant at 95% C.L given in figure 7.

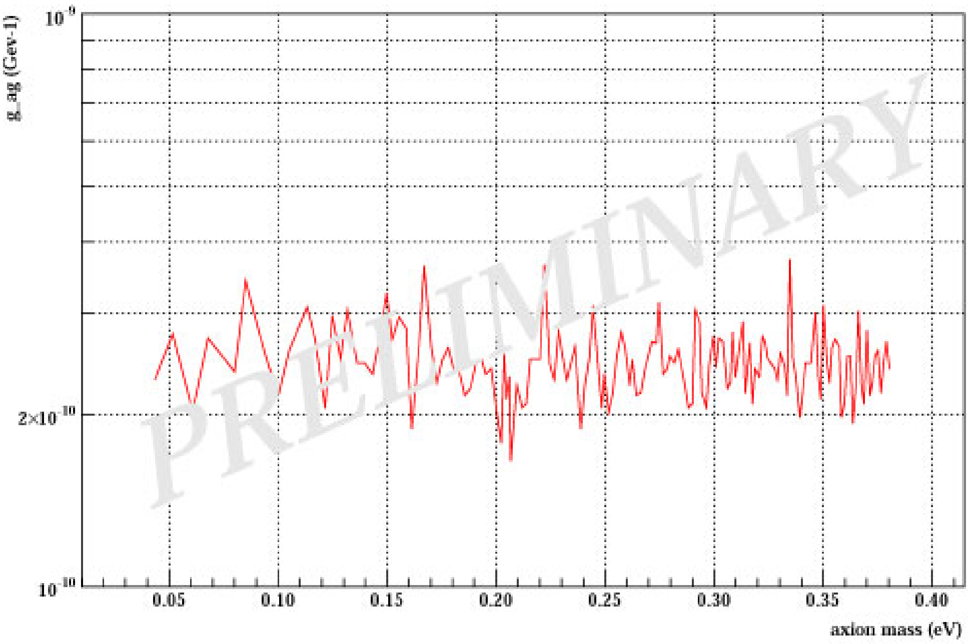

Figure 7: Preliminary limit on the axion-photon coupling constant (95% CL) for the Micromegas phase II data.

2.6. TPC operation

The Time Projection Chamber (TPC) of the CAST experiment operated continuously during the data taking of CAST second phase.
The development the new differential windows made of 4 μm polypropylene foil has reduced the leak rate of chamber gas towards the magnet compared with phase I.

2004 LEAK RATE
$\Phi(Ar) = 1.46 \times 10^{-7}$ mbarl/sec
$\Phi(CH4) = 4.6 \times 10^{-8}$ mbarl/sec

⇨

2005 LEAK RATE
$\Phi(Ar) = 2.9 \times 10^{-8}$ mbarl/sec
$\Phi(CH4) = 1.3 \times 10^{-9}$ mbarl/sec

The system decreased by a factor 690 the leak rate for Ar and a factor 700 for CH_4 related to the leak rate of the TPC detector. Second phase setup improves a factor 5 for Ar and a factor 35 for CH_4 related to the best leak rate measured in 2004. This improvement has become crucial in CAST second phase, due to the existence of the cold X-ray windows whose cold surfaces can cryo-pump residual gas molecules during the run and so eventually reduce the X-ray transmission of the windows.

The installation of a passive shielding that was already installed in 2004 has been reproduced for the second phase of CAST and the final shielding configuration for the TPC detector is composed of several layers of material in order to reduce the experimental background. The final setup of the shield it is composed by 225 mm of polyethylene, 1 mm of cadmium, 25 mm of lead and 5 mm width copper box covering the TPC detector. A purge of nitrogen inside the copper box creates an over pressure which helps, together with the plastic bag sealing the whole structure, to decrease radon contamination.
Figure 8 shows the effects of the different layers of shielding in the 2006 background of the TPC detector and figure 9 the independence of the background for the TPC detector with its definition.
The data of the TPC detector are currently analyzed and the first approaches to get a limit on the coupling constant $g_{a\gamma}$ have been done. A completely new code has been written in order to implement the absorption of photons in the gas due to different processes (photoelectric effect, Compton and Rayleigh scattering).

Figure 10 shows a preliminary result for the first 123 pressure settings in the ^{4}He run, as well as a very preliminary combined result for the phase I and phase II data.

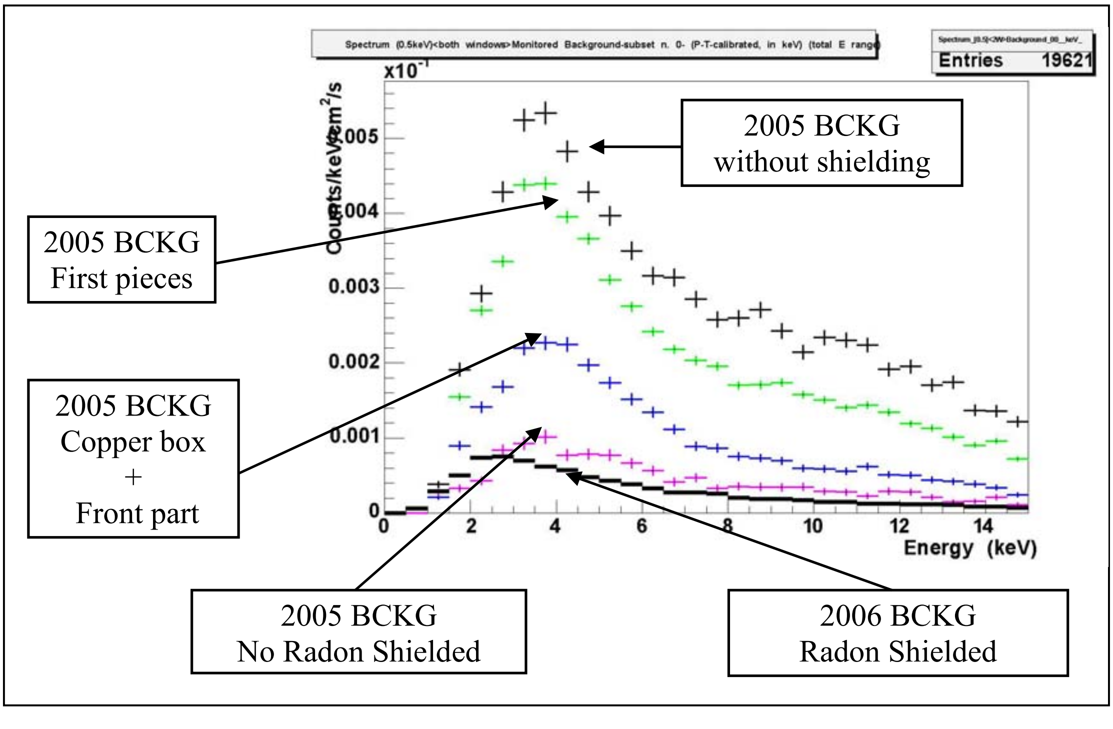

Figure 8: Comparison between the different levels of background that the TPC has related with the different steps of the shielding installation.

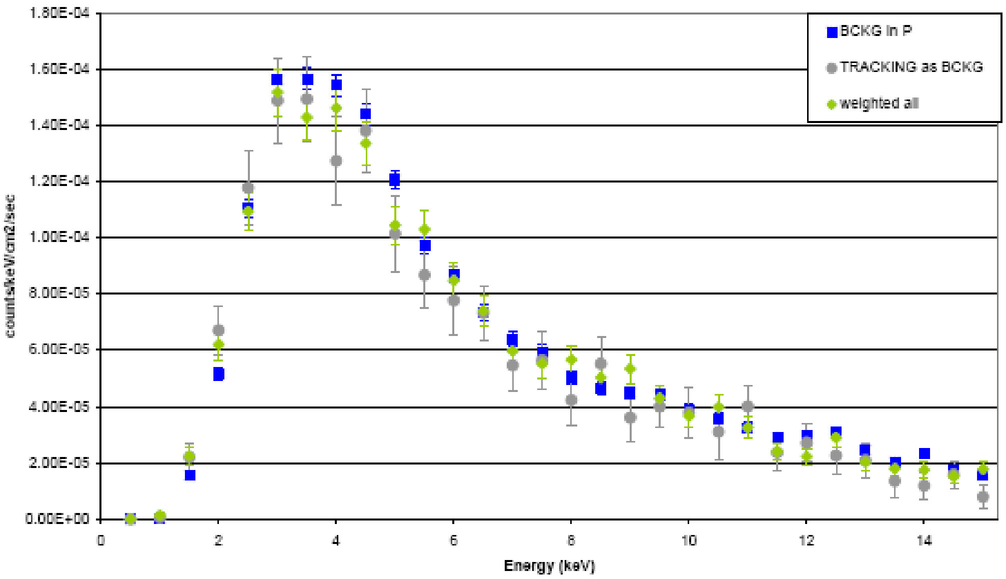

Figure 9: Comparison of different backgrounds. Stability of the detector background is independent of the position.

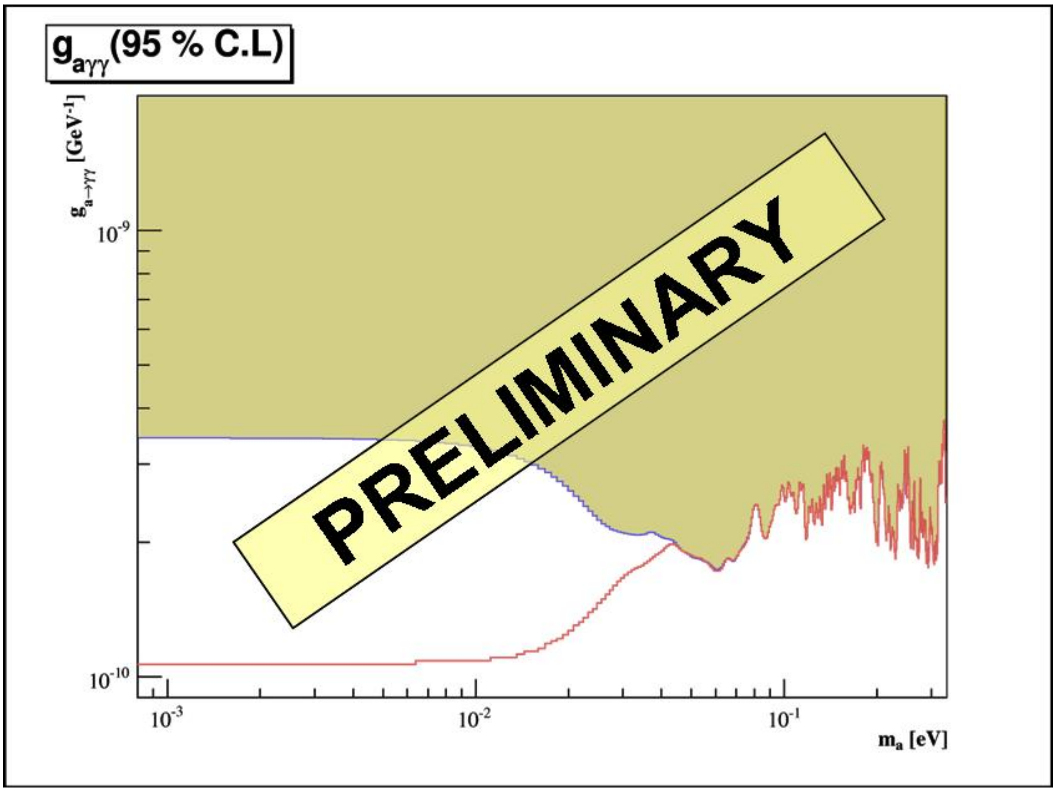

Figure 10: Preliminary limit on the axion-photon coupling constant (95% CL) versus axion mass for the TPC phase II data (blue line) and combined phase I and phase II data (red line).

3. Prospects for phase II ^{3}He run in 2007

The final gas system with ^{3}He gas is presently under construction and will enable the search of axions up to the saturation pressure of ^{3}He (135.58 mbar @ 1.8K), 10 times higher than that achieved by the ^{4}He gas system. The 2007 data taking is scheduled to start by the middle of August. The new system will allow two density settings per tracking enabling CAST to reach a value of about 30 mbar @ 1.8 K by the end of 2007. In what follows, the ^{3}He gas system status is presented, followed by the status of the new Micromegas line. The conclusions of the safety review of the magnet movement are presented at the end of the section.

3.1. ^{3}He gas system status

The ^{3}He gas system presents two major challenges: the accuracy required in measuring the quantity of gas introduced into the cold bores, and the need to build the system so as to avoid any loss of the expensive gas.

The data taking runs with ^{4}He provided essential input for the design of the ^{3}He gas system, described in the Technical Design Report (CERN-SPSC-2006-029). The ^{3}He TDR was successfully reviewed by an expert Review Committee in October 2006. The preparation and submission to the review process proved to be a useful process, and whilst no technical faults were found in the review, some technical and operational suggestions and several safety recommendations were incorporated in the final design.

The final design of the ^{3}He gas system contained major improvements relative to the ^{4}He system. Principally, the mechanism for changing the density has been made extremely flexible. Firstly, there is the possibility to make two density steps per day, either by changing the density before tracking or in the middle of the tracking run. Secondly, there is the possibility to ramp at constant speed the gas density up or down during the tracking period, covering a maximum of 10 steps during the run.

The number of density settings has been optimized to maximize the discovery potential, the optimal density step corresponding to a pressure difference of ~0.1mbar at 1.8K, or about one FWHM of the mass distribution at a given density. The possibility to make double stepping per day comes from the need to shorten the data taking period to exploit the full available range with ^{3}He before the end of 2010. These new operation modes also allow the experiment to be more flexible in case of a potential signal or the need to reject that hypothesis, allowing an easy way to revisit a given density setting or to make smooth scans around a density region.

Based on the experience gained during the operation with ^{4}He, and on the quench tests before constructing the ^{4}He gas system, the main requirements for the design of the ^{3}He gas system have been set: safety against loss of ^{3}He, accurate metering of the amount of ^{3}He in the magnet bores, absence of thermo-acoustic oscillations and protection of the cold thin X-ray windows during a quench. Figure 11 shows the main features of the system in a schematic diagram.

The system philosophy is to have a closed hermetic circuit, divided in 4 sections: the storage region where the necessary inventory of ^{3}He contained, the metering region where the quantity of gas sent to the cold bore is accurately measured, the cold bore region where the gas is confined and maintained at stable density, and finally the expansion region for a fast recovery of the gas in case of quench. The last section has been designed in order to maintain the pressure in the cold bore below 1.2 bar (including safety factors) during a fast magnet temperature increase.

The cold X-ray windows must withstand any pressure difference that develops between the cold bore gas and the vacuum in the beam lines leading to the X-ray detectors. A recent test made in the CERN Cryolab at 60 K on an identical window to those installed in CAST has successfully withstood repeated rapid pressurizations up to 3 bar. The maximal static pressure applied was 3.5 bar, limited only by the instrumental pressure limits of the cryogenic system. The window strongback deflections were measured by a sensitive displacement probe and no evidence of plastic deformation was observed.

For comparison, the maximum pressure that can develop in the cold bore after a magnet quench in the case that all safety systems fail is estimated to be 1.25 bar (end 2008) and 2.5 bar (end 2010). These tests give us confidence on the robustness against any loss of ^{3}He while reusing the present windows. The window development is nevertheless continuing and at present a project is underway which combines ANSYS modeling and material and window testing at low temperatures with the aim of understanding the high pressure behavior of the windows in order to optimize the windows for operation at the highest pressures to be encountered in several years time.

The integration of the new ^{3}He gas system requires major modifications inside the cryostat. The existing gas lines have to be completely modified requiring significant integration studies in order to mount the cryo-valves, check valves and a rupture disk inside an already crowded volume. Outside the cryostat the full system of the expansion, storage and metering vessels, plus vacuum pumps, and instrumentation needs to be installed. Only the essential components will be mounted on the magnet to limit the additional load. The remainder will be installed in close proximity to the main pivot and connected by double walled flexible lines to the magnet.

The month of January was used for warming the magnet to ambient temperature, breaking the vacuum and preparing the zone by mounting safety structures on both ends of the magnet. The 3D modeling of the gas lines inside the cryostat allowed us to conceptualize the integration of the new components on the very limited space available, but nevertheless after the opening of the cryostat some changes had to be done in the initial plan. During the month of February, upon the arrival of the main cryogenic valves the new lines could be pre-assembled, the old pipe-work was removed to allow a better access to the regions to be modified and the regions inside the cryostat protected. During this time the modeling of the integration of the new components continued.

The last month of March was marked by the intervention needed inside the cryostat on both sides, including cutting and welding of several pipes, introduction of a new feed-through in the cold bore for a new cold pressure transducer. In addition, the magnet LHe cooling line had to be re-routed (and then pressure tested) to allow the passage of the body a new cryo-valve. New flanges were installed on the cryostat to allow the passage of the new valves. The storage volume was assembled and tested, and the expansion volume components produced.
The month of April will be marked by the assembly and leak testing of the lines inside the cryostat, and the assembly of the large volumes of the system outside the cryostat.
During this time the control system has been conceptualized, to include all the safety and routine operating modes, the size of the PLC has been established and the ordering of components started.

The present schedule foresees the work inside the cryostat at both ends of the magnet, to be done in parallel with the work outside the cryostat and to last until the middle of May 2007, the cool down of the magnet to start in June and the commissioning phase first with ^{4}He and finally with ^{3}He to be finished by the middle of August 2007.

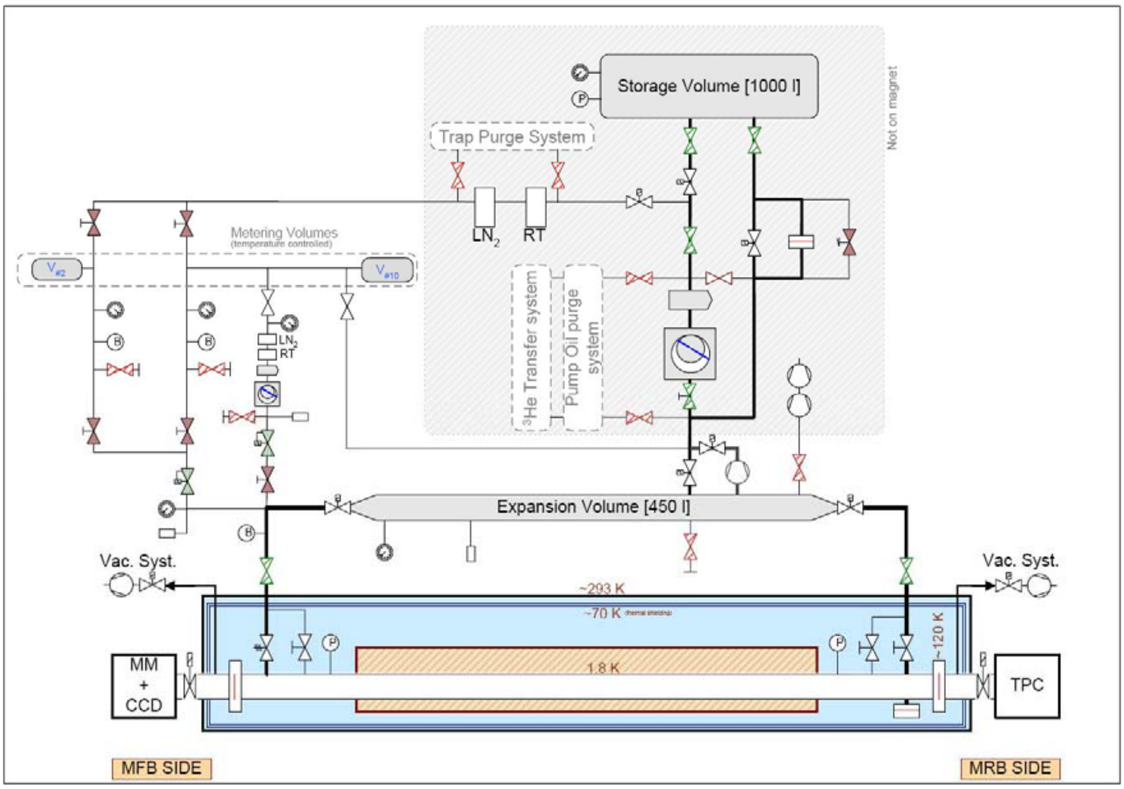

Figure 11: Scheme of the ^{3}He gas system

3.2. New Micromegas line

During the preparation of the magnet for phase II, the Micromegas group took the opportunity to design an upgraded Micromegas line as shown in figure 12. The main novelties concern the integration of an X-ray optic and the implementation of a passive shielding. These upgrades should improve significantly the performance of the detector. First, the X-ray optic, a concentrator with a 1.3 m focal length and 47 mm diameter, should allow us to increase the signal to noise ratio by a factor 100 by focusing the photon flux in a few millimetres spot. This concentrator consists of 14 nested polycarbonate shells, each 125 mm long and coated with iridium. The optic was designed to transmit 36% of the 0.5-10 keV flux emerging from the magnet bore. Second, the shielding, composed of copper, lead, cadmium, nitrogen and polyethylene, is expected to reduce the background by a factor of 4. Third, by changing the gas of the chamber from Argon to Xenon, the photon conversion probability can be improved by at least 10%. This detector will be running with the same electronics and acquisition developed for phase I.

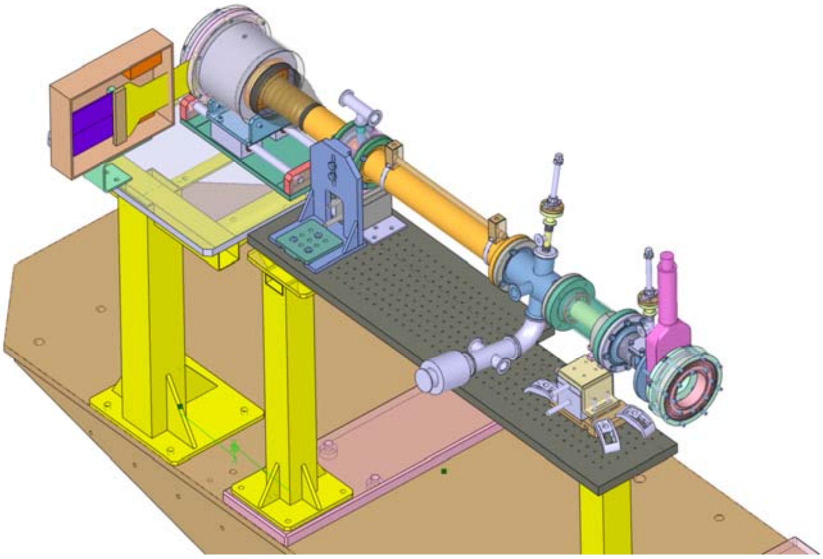

Figure 12: A schematic picture of the new Micromegas line with the detector in the Faraday cage surrounded by the shielding.

The detector was tested at the laboratory and the complete line with the integrated optic was tested at the PANTER X-ray test facility in Munich in September 2006. A photo of the set-up is shown in figure 13.

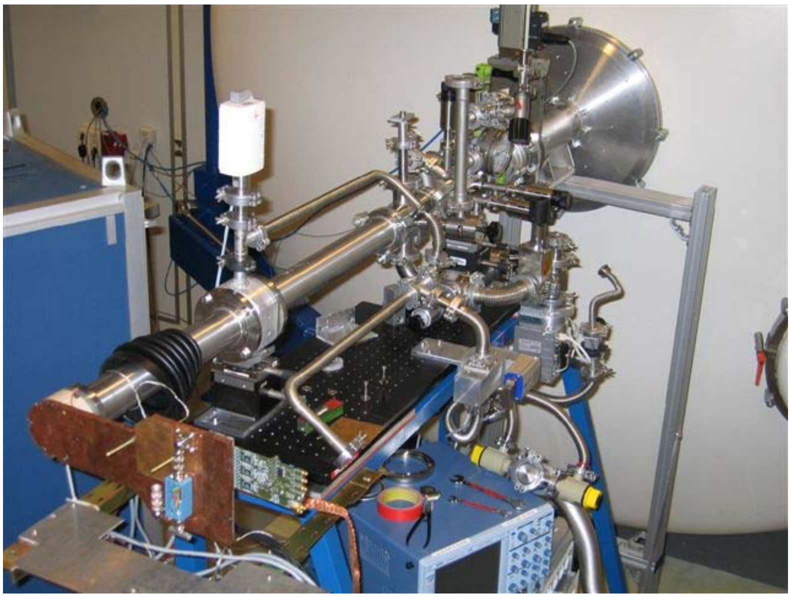

Figure 13: The Micromegas line in the PANTER X-ray facility.

The aim of this test was first to characterise the concentrator measuring the focal length, the point spread function and the throughput (effective area). Secondly to couple the concentrator to the detector and measure the end-to-end performance.

The test was very useful in providing experience in the alignment procedure and in giving hints for the improvements of the integration of the line. The collimator did not meet the specifications. The focal length was measured to be 1.4 m, longer than expected due to manufacturing errors of the shells. In addition the measured throughput was much lower than the modelled performance. This difference comes from geometrical errors on the shells, larger than expected roughness on the reflective coatings and likely, some contamination. Figure 14 shows a comparison of the measured data and the simulation of these effects. It can be observed that the behaviour of the optics is quite well understood. Work is in progress to correct geometric errors and to improve the quality of the coating. We continue to investigate the nature of the putative contamination. A second optic is under construction and the full line will be retested at PANTER before installation in the CAST experiment.

In the eventuality of the optic not being ready for the 2007 data taking, we are studying a back-up solution with the possibility of adapting the previous detectors to be able to accommodate a passive shielding like the one described above. Tests are being done at the moment (end March-April) in the CAST hall to estimate the gain in background reduction with the Micromegas detector used in the 2006 data taking surrounded by the TPC shielding. Figure 15 shows two photos of the set-up.

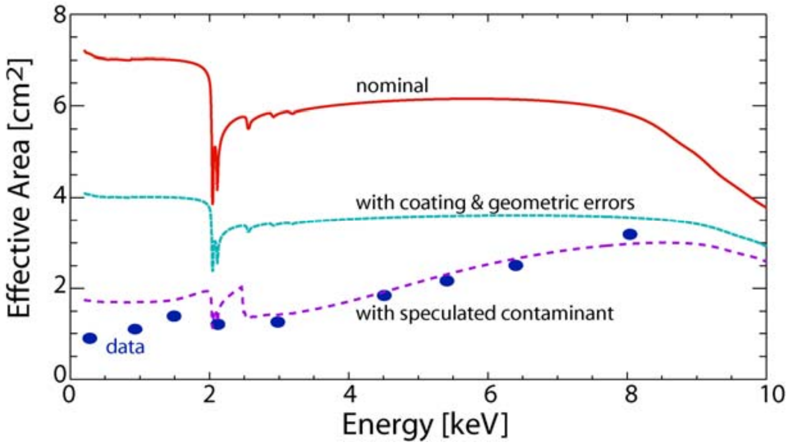

Figure 14: Effective area (throughput) as a function of energy. The red line shows the nominal effective area. The green line shows the throughput after accounting for geometrical and coating errors, while the purple curve shows the additional reduction that could result from a contamination layer on the optic.

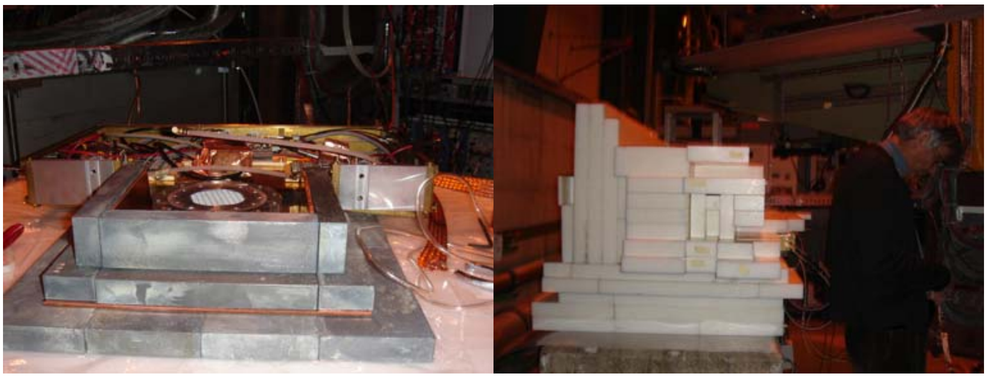

Figure 15: On the left, the Micromegas detector dismounted of the CAST magnet lying on a concrete block and partially covered by copper and lead. On the right, final set-up of the shielding test with Micromegas detector completely covered by copper, lead, polyethylene (white blocks).

For next year, we are envisaging upgrading the electronics to be able to reconstruct a track completely by adding the time information. This should result in a further reduction of the background. We are exploring different existing electronics that could suit the Micromegas CAST applications. Among others, the recent developed T2K electronics developed for the Micromegas detector in this experiment could be a solution as well as the APV25 or PACE V3 (developed for the tracker and the preshower of CMS). Feasibility tests in the next few months should lead to the chosen solution by the autumn.

3.3. Magnet movement safety review

The magnet movement system continues to provide magnet pointing accuracy within the 1 arc minute tolerance required for CAST. However, in view of the addition of extra loading on the magnet in the form of the ^{3}He system and additional safety rails (an additional 1.2t on a total of 55t) and the extended running time is between 2008 and 2010, it was timely to make a safety review of the magnet movement system. This review, using the expected final loads, was to provide up-to-date calculations and information, together with a series of proposals for safety modifications to structures. This will provide the required basic information to base future engineering support by the TS-MME group as requested by CAST.

A consultant engineer J. Blocki from Cracow University made the safety study in February 2007 and presented the results to a group of CERN engineers from TS-MME, SC and PH Departments. The conclusion of the report and related discussions were:

- Two known weak points on the lifting frame (‘chariot’) should be strengthened before the 2007 run. The report proposed simple and practical methods to do this.
- The main vertical pivot axes are within 5% of the maximum loading after all safety factors are included and a conservative assumption is made of both the load distribution at the bearings and also the mechanical properties of the steel. Fatigue was not found to be a problem, the total number of cycles of the vertical movement will not exceed 4000 by the end of 2010 whereas the threshold for fatigue is estimated at ~ 70 000 cycles. Two different approaches were then proposed to improve safety :
  1. Increase significantly the safety margin by replacing the axes with higher performance steel and an improved profile. However there are potential difficulties to extract and to reinsert these axes and the consequences for the pivot alignment and the subsequent magnet pointing accuracy are unknown.
  2. Assume that the current pivot support frames, bearings and axes accommodate together to minimize the forces and that the present known cinematic behaviour is preferable to the unknown. In this case, the consequences of a failure of the pivot axes must be studied and where necessary, mechanisms installed to prevent danger to personnel and limit damage to equipment in the event of a failure.

CAST will make all necessary modifications to the chariot in the next 3 months and will follow the second alternative for the main pivot. In addition, analyses of the material of the axes are in progress to define the composition and micro-hardness of the steel which is potentially 16% stronger than that assumed in the study.

4. Request for extra running time

The CAST Collaboration is requesting an extension to CAST running time for the years 2008, 2009 and 2010.

In the previous sections, we have shown the steady progress of the CAST experiment. With the new, sophisticated ^{3}He gas system, the CAST Collaboration is confident that the operation will be possible up to at least 120 mbar @ 1.8 K. In this way, CAST would be able to explore a very interesting region of axion masses up to 1.16 eV.

In what follows we present a physics justification for this request, as well as some details of the running time, costs and resources required.

4.1. Physics justification

For axions, the ratio between mass and photon-coupling is given, up to model-dependent numerical factors, by the corresponding pion properties. This ratio defines the "axion line" in the parameter plane of mass and photon coupling strength. The gas-filling phase of CAST will allow us to extend our sensitivity up to masses of about 1.1 eV and thus to "cross the axion line". This will be the first experiment to reach a sensitivity where the existence of "invisible axions" is tested. All previous experiments, including the CAST vacuum phase, were only able to search for generic axion-like particles with masses much smaller than would be expected if they are indeed responsible for solving the strong CP problem.

Axions with eV-range masses would have thermalized in the early universe by their generic pion interactions and thus contribute a hot dark matter component of the universe, similar to neutrinos. The usual structure-formation limits on neutrino masses therefore can be translated into analogous limits on axion masses. Limits of this sort, of course, depend on systematic uncertainties of the cosmological standard model. At the present time, these limits reach approximately down to 1 eV. Therefore, if CAST II can close the gap to ~1 eV from below, and assuming that in future the cosmological limits will reliably reach down to 1 eV or even somewhat below, a seamless coverage of all axions masses will be achieved down to the axion-photon coupling limit that is achieved by CAST II. Figure 16 shows the expected contribution that CAST can make in this field.

There is an ongoing burgeoning interest in the axion and in pseudoscalars beyond Standard Model physics more generally. Indeed it can be said that there has never been so much theoretical and experimental activity in axion physics since its prediction in the late 1970s with the original papers of Peccei and Quinn, Weinberg and Wilczek.

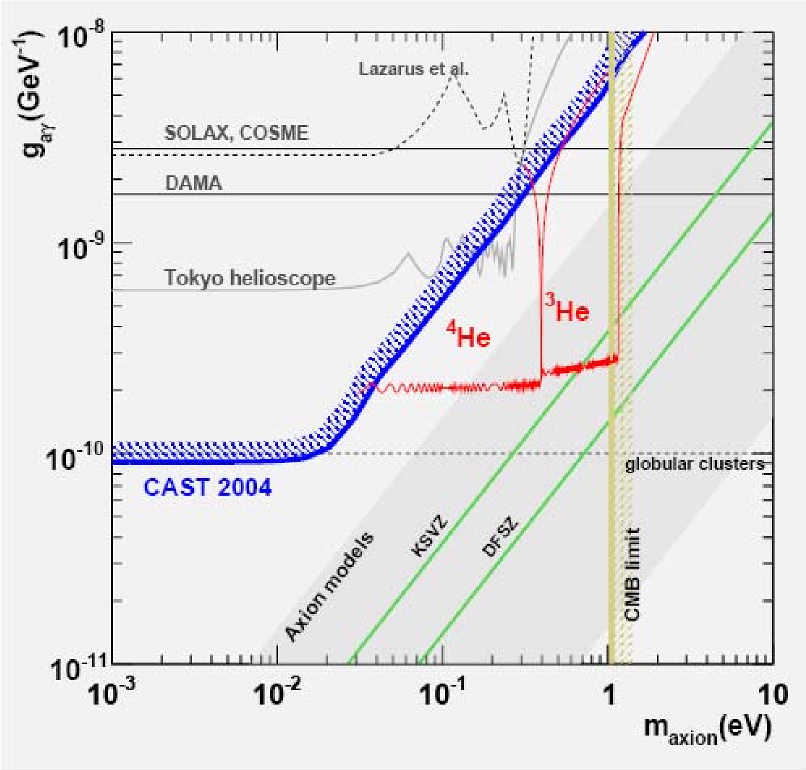

Figure 16: CAST prospects, scan up to 120 mbar @ 1.8 K

There are several factors contributing to this remarkable renaissance. The Peccei-Quinn mechanism that protects the strong force from CP-violating effects and results in the axion, has endured for thirty years, and is widely regarded as the best and most attractive solution to the strong-CP problem. Additionally, axion is one of the two outstanding candidates to constitute the dark matter of the universe, along with the neutralino or other WIMPs. Furthermore, there is now serious attention being paid to axion by string theorists. The situation may be summarized by saying that axions or axion-like particles are a generic feature of string theories, and it seems that there should be at least two, and possibly of order a hundred, pseudoscalar particles within any particular string theory. In his summary talk at the recent workshop "Axions at the Institute for Advanced Study", Ed Witten mused that axions may even be intrinsic to the very structure of string theories.

The most important factor fuelling this interest, however, is the rapidly growing experimental effort in axion searches: CAST at CERN looking for solar axions, ADMX in the U.S. and CARRACK in Japan looking for dark matter axions, and more than half a dozen photon regeneration projects and proposals in various stages of preparation to check the remarkable claim of magnetically-induced vacuum birefringence and dichroism by the PVLAS collaboration in Italy. These

efforts span a large area of mass and coupling space, in part overlapping and in part complementary. The theoretical and phenomenological situation is quite confused, with no clear convergence on the axion parameters. This situation should be viewed as an opportunity rather than discouragement to the experimenter - it tells us that the unknown facts outweigh the known facts and assumptions required by cosmology, astrophysics and underlying theory. In these circumstances the experimentalists should cast the net widely and be open for surprise. We are on the cusp of discovery, perhaps not only of the axion, but an entire sector of pseudoscalars.
In the ApPEC roadmap it is recommended that **"the CAST experiment should be continued to cover the full range of axion masses that is accessible by this technique"**.

In addition, as a tuning experiment planning to explore the axion mass region up to ~1.1 eV, CAST would also be sensitive to the existence of large extra dimensions, introduced in the world-brane scenarios to solve the hierarchy problem in particle physics. The detection of X-rays at least in two gas-pressures inside the magnetic pipes can be the potential new signature of (two) large extra dimensions with the compactification radius down to around 170 nm.

Other perspectives: Low energy solar axions

For some unknown reason(s), the temperature of the upper solar atmosphere (the corona) increases to a few10^6K, while the underlying photosphere is ~200-300 times cooler. This is known since 1939 as 'the solar corona problem'. The direct detection of solar X-rays came in the late 1940's. In the 1950's the first images of the quiet X-ray sun were made, while Elwert developed models explaining partly the X-rays from the quiet and active sun. Since then more than 10 categories of models have been proposed, but the mechanism that heats the solar corona remained elusive, and it is "one of the most important problems in astrophysics".

Contrary to the solar axion model, the solar X-ray observations may favour the direct search for axions also at low energies, since they may be the mechanism behind the mysterious quiet sun soft X-rays. CAST has the potential to search for the first time for solar axions in the ~1–1000 eV range, a region which has not been addressed before either experimentally (due to energy threshold) or theoretically (due to the presence of plasma effects up to ~300 eV). In the range of a few 100 eV to 1 keV, CAST is already investigating with the ongoing analysis of data taken with the CCD detector.

With CAST's working principle reversed, solar axions can be coherently created in the ~1-10 eV range near the solar surface. Sunspots with measured magnetic fields reaching ~0.5 Tesla seem particularly attractive, while magnetic fields are not included in the solar axion model. Also, if the sunspot enigmatic origin is due to the involvement of axions or other particles with similar properties, the required coupling strength must be much larger than expected for QCD axions. For comparison, we use below PVLAS derived parameters[1].

In a direct low energy solar axion search, CAST could also see a signature, if the particle interpretation of PVLAS is correct. If the CAST data taking period is extended, CAST could perform short runs of ~1 week, without affecting the actual base program. They require only moderate resources and there is interest from external groups to participate in this type of measurement.

4.2. Details of running time, costs and resources required

4.2.1. Running time

The ^{3}He intervention and cool-down will take place in the 1H2007. At the start of the 2H2007 there will be a commissioning phase with first ^{4}He and then ^{3}He in the gas system. The commissioning phase will include tests of the several different metering modes implemented in the system (see TDR pages 10-11 and 31-39). The gas density can simply be increased before the sunset tracking to change the setting by one step each day for each detector (as before) or, the density quickly changed by one step in the middle of a solar tracking run or, the density can be uniformly ramped (up or down) across a range equivalent to about one step during the tracking. After thorough testing, the optimal metering mode will be identified and adopted for the data taking phase which should then occupy about 4 months until to the end of 2007. It is expected that at the end of 2007 the scan will reach about 30 mbar @ 1.8K (axion rest mass of 0.58 eV).

In 2008, 2009 and 2010 we assume here that at the start of each year there will be a medium-sized intervention to either inspect or change cold X-ray windows or make additions to instrumentation or repairs inside the cryostat. In parallel, the annual maintenance will be scheduled for the CAST experiment and cryogenics. In reality, the shutdowns will be synchronized with the LHC shutdowns wherever possible to maximize running efficiency. Additional overheads come from

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[1] Numerical Example: we consider a depth of ~90 km below solar surface, with a mean photon energy of ~2.2 eV. For a photon mean free path length λ=1700 m and an axion rest mass of 10^{-3} eV [=plasma frequency energy for 1% level of ionization], the effective layer thickness is ~3 km for ~0.3% density change. The mean number of photon collisions is equal to 1.65. The estimated axion luminosity is given by the axion-to-photon conversion efficiency times the solar luminosity:

$$L_{axion} \approx 1.36\text{x}10^{24}\ \text{erg/s} = 2\text{x}10^{9}\ \text{axions /s/CASTexit}$$

assuming a filling factor of 0.1%, B=0.3 Tesla and $g_{a\gamma\gamma}=2.5\text{x}10^{-6}\ \text{GeV}^{-1}$. In the CAST magnet, the back conversion efficiency of ~2.2 eV axions to photons is ~$6\text{x}10^{-10}$**,** for a coherence length of ~2 m and using again the same PVLAS derived axion-to-γγ coupling constant. The expected axion signal rate (S) of photons of 2.2 eV is **S = 1.2 Hz**. In the UV (e.g. at ~6.6 eV), the signal rate increases to S ≈ 3.6 Hz, with the coherence length in CAST being 6 m. For comparison, the signal rate from a solar depth of 200 km improves slightly (1.6 Hz instead of 1.2 Hz), for the allowed layer thickness being 25 km, λ=260 m, number of photon collisions being equal to 175 and photon energy ≈ 2.6 eV. This improving signal at slightly bigger depths and at higher photon energies makes such measurements sensitive to a wider layer thickness of the Sun, which might imply a kind of built-in tuning to the actual axion or axion-like particles CAST may be, alternatively, sensitive to observe.

pumping, warming or cooling down of the magnet. There are also number of other tasks to schedule, namely alignment of the X-ray telescopes and general alignment of the CAST magnet (GRID).

The estimated number of calendar days for data taking runs in 2007-2010 is shown in table 1. The number of tracking days is assumed to be 80%[2] of calendar days and includes quenches, window bake-outs, sun–filming, X-ray finger alignment runs and the condition that at least two out of the three X-ray detectors are functioning correctly during the tracking.

The number of pressure settings was optimized to maximize discovery potential; the optimal density step corresponding to a pressure difference of ~ 0.1 mbar or about one FWHM of the mass distribution at a given density (TDR pages 3 & 10). In the ~ 630 tracking days in 2007-2010, it is essential to cover at least 0.2 mbar each day by either introducing a metering step mid-tracking or making a smooth ramp over a metering step during the tracking. With the assumption of ~0.1 mbar per step, a maximum pressure of 135 mbar (saturated vapour pressure of ^{3}He) can be achieved by the end of 2010.

Year	Calendar days	Tracking days (80%)	Pressure range covered with: One step mid tracking or Ramp of ~0.2 mbar (mbar @ 1.8K)	Pressure range covered if also include a search protocol (mbar @ 1.8K)
2007	126	100	13.4 – 31 (0.39 - 0.59 eV)	13.4 -29 (0.39 - 0.56 eV)
2008	220	176	31 – 65 (0.59 - 0.85 eV)	29-57 (0.56 – 0.80 eV)
2009	220	176	65- 102 (0.85 - 1.06 eV)	57- 88 (0.80 – 0.99 eV)
2010	220	176	102- 135 (1.06 –1.22 eV)	88-120 (0.99 – 1.16 eV)

Table 1: 2007 to 2010, running time available in calendar days, tracking days after normal losses, and pressure ranges (with corresponding axion rest mass ranges) achievable each year.

To search for small signals amongst background fluctuations, a simple real-time protocol can be triggered using the results of a fast CCD/telescope analysis for hits in the CCD fiducial area. This protocol would then entail remaining at the same density setting until a ‘signal’ hypothesis is rejected. Such a protocol with the existing CCD-telescope requires an additional 15% running time and the reduced annual pressure coverage that would result is shown in the last column of table 1. With the addition of a second X-ray optics (MicroMegas Line) on the sunrise side, this additional time would be reduced or the same time could be spent on extending the search to smaller signal levels.

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[2] The 80% efficiency figure is derived from experience gained from taking run in 2005-2006.Quenches (~10 per year, 1 day each), window bake outs (~ 8 per year, 3 days each), infrastructure failures, sun–filming, survey GRID and X-ray alignment runs. This efficiency decreases from 80% to 70% if the CCD data is required to be present at all pressure settings.

The strategy for the CAST data taking will be a continuous ascending pressure scan. Operating with a buffer gas-filled cold bore is unexplored territory for CAST and there is a learning curve to experience and effects to understand as the density continues to rise (e.g. window cooling effects due to the coupling of the windows to the cold bore via the buffer gas). Successive small steps are the best way to maximize the discovery potential (e.g. as opposed to missing every second step and returning later). CAST also prefers not to leave large gaps at lower density in order to target the maximum density region first.

CAST is interested to run to the limit of the capabilities of the ^{3}He system which will take 3 years to achieve. CAST is making a feasibility study on how to make a significant increase in the sensitivity of the experiment (replacing some detectors with lower background versions, augmenting the number of X-ray optics and improving the X-ray detection efficiency).

4.2.2. Costs and resources for CERN

Magnet Running Costs

The costs for CERN of this extension in 2008, 2009 and 2010 for the operation of the magnet are the usual electricity costs for the cryogenics and magnet power converter and the M&O costs of the cryogenic support team.

Item	**Dept**	**Units**	**2008**	**2009**	**2010**
Cryogenics M&O (incl gases)	AT	(kCHF)	180	180	180
Cryogenics power		(hours)	6250	6250	6250
	TS	(kCHF)[3]	172	172	172
Magnet Power Converter		(hours)	4700	4700	4700
	TS	(kCHF)[3]	34	34	34
Power Converter Field Support	AB	(kCHF)	3	3	3
	CAST	(kCHF)	3	3	3
Annual Total AT/TS/AB		(kCHF)	389	389	389
Integrated Total AT/TS/AB		(kCHF)	389	778	1167

Table 2: Estimates for the cost of running the CAST magnet 2008-2010.

Manpower

The CAST collaboration relies on the expert technical support from the Technical Departments at CERN, for which CAST it is very grateful. In 2007, the AT Department and in particular the AT-ECR group has made an exceptional effort to help CAST build the ^{3}He system. For the following years, 2008-2010, CAST will require continued support from the Technical Departments at a level similar to that already provided in 2005 and 2006. The future support of the PH

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[3] Calculated assuming 55 CHF/MW

Department is also essential, as it has been in past years, for financial support and manpower to manage and run CAST and for technical support for the experiment and the fabrication of the cold X-ray windows.
The manpower and financial requirements for CERN support to CAST for 2008-2010 are shown in the following tables together with the year 2007 for reference. The requests have been formulated into work packages or jobs (TS/MME) and have already been circulated to the groups concerned and will be finalized in the coming months.

		2007		2008		2009		2010	
Dept.	Group	Engineer Physicist	Technician	Engin Phys.	Techn	Engin Phys.	Techn	Engin Phys.	Techn
		(FTE)	(FTE)	(FTE)	(FTE)	(FTE)	(FTE)	(FTE)	(FTE)
AT	AT/ECR	0.95	0.85	0.45	0.05	0.45	0.05	0.45	0.05
	AT/VAC	0.15	0.1	0.1	0.05	0.1	0.05	0.1	0.05
	AT/ACR	0.05	0.1	0.05	0.07	0.05	0.07	0.05	0.07
	AT/MTM		0.05		0.05		0.05		0.05
	Total	***1.15***	***1.10***	***0.60***	***0.22***	***0.60***	***0.22***	***0.60***	***0.22***
AB	AB/PO & CO	0.02		0.02		0.02		0.02	
TS	TS/MME(Design paid by CAST)	0.2		0.2		0.2		0.2	

Table 3: Manpower requirements requested from AT/AB/TS Departments.

	2007		2008		2009		2010	
	(FTE)	(kCHF)	(FTE)	(kCHF)	(FTE)	(kCHF)	(FTE)	(kCHF)
Technical Coordinator	0.9		0.75		0.6		0.5	
Applied Fellow	1		1		1		1	
Spokesman	0.5		0.5		0.5		0.5	
FSU mechanic	(0.5)		(0.3)		(0.3)		(0.3)	
Technician	0.2		0.2		0.2		0.2	
Exploitation (incl. FSU costs)		110		110		110		110
Total	***2.6***	***110***	***2.45***	***110***	***2.3***	***110***	***2.2***	***110***

Table 4: Manpower and financial request to the Physics Department

4.2.3. Costs to CAST and a Future Addendum No 3 to the CAST MOU

The funding of the extension for 2008-2010 will be detailed in an Addendum No 3 to the CAST MOU to be completed by the end of 2007. The first estimate of the costs of running CAST with the present set of detectors and making only moderate interventions and improving essential instrumentation requires a sum of about 600 kCHF for 2008-2010 (see below), which corresponds to ~12 kCHF per member (post-doc and above) of the present Collaboration of CAST phase II. The Collaboration works towards upgrading the detection system and improving the sensitivity of CAST and a first estimate of the likely cost is 225 kCHF. If the total cost were to be shared across the Collaboration, it would increase the per capital contribution from about 12 to about 16.5 kCHF per member (post-doc and above). Meanwhile, the institutes directly involved with detector upgrades will apply for additional contributions to these projects from their funding agencies.

2008-2010 General M&O		450	kCHF
Instrumentation & Safety		150	kCHF
	Sub total	600	kCHF
New optics		125	kCHF
2 New MM detectors + design + electronics + shielding		100	kCHF
New CCD detector with low energy threshold		150	kCHF
	Sub total	375	kCHF
	Total	**975**	**kCHF**

5. Conclusions

The present status of the CAST experiment has been described. The preliminary results of the ^{4}He data analysis show that the predicted limit on the axion-photon coupling constant is reachable. The sophisticated ^{3}He gas system has been designed and constructed with a substantial amount of R&D. CAST will take data with ^{3}He inside the magnet bores during the second half of 2007.

In view of the growing interest in axion physics, and in order to fully exploit the discovery potential of the phase II gas system, CAST plans to extend the operation of the experiment at CERN beyond its present approval to cover the years 2008, 2009 and 2010. The Collaboration is requesting this extension to be recommended by the SPS Committee for the approval of the Research Board. This extension would enable to take significant amount of data in the most interesting range of axion masses between 0.59 eV and 1.16 eV.