CAST Status Report to the SPSC for the 123\textsuperscript{rd} Meeting

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1 Summary

After the successful 2015 data taking with Micromegas detectors, targeting solar axion search, and with an InGrid detector, targeting solar chameleon search, CAST has started on its new 2016-2018 program which has been presented to SPSC at the 119\textsuperscript{th} meeting in October 2015. This program extends the physics goals of CAST towards the search for solar chameleons using a force sensor (KWISP) and towards the search for relic axions using a microwave cavity inserted into the CAST magnet (CAST-CAPP). The search for solar chameleons and other axion-like particles was continued with a significantly upgraded InGrid detector. The new experiments make use different elements of the unique CAST infrastructure (KWISP: Abrixas XRT and sun pointing capability of CAST, CAST-CAPP: high magnetic dipole field), while the InGrid detector exploits all of CAST’s features (Abrixas XRT, high magnetic dipole field, sun pointing). All three experiments within CAST have made significant progress in exploring these new approaches in 2016 which are reported here. Furthermore, the analysis of 2015 Micromegas and InGrid made good progress and is approaching finalization and publication.

2 Status of CAST Infrastructure

2.1 Report from Technical Coordination

Cryo & ABB Upgrade
All the programmed upgrades have been completed and allowed afterwards the magnet to be cold without problems. The first half of the year in 2017 the second half of the upgrade will be performed, which would bring the cryo-system up state of the art compared to the LHC magnets.

Sun tracking with the first KWISP prototype
We took data during 9 mornings end of April including some low frequency chopper variations before dismounting KWISP to leave the space for InGrid. Analysis is ongoing.

Preparation of data taking with Ingrid for summer/autumn run
The preparation of InGrid was performed in Bonn during all year, which allowed us to install it at CAST on schedule. All planned detector r/o systems and veto-scintillators have been used for about 10 days of sun tracking data taking. Afterwards we found a misbehaviour in a HV line (a short), which obliged us to dismount the detector and to ship it back to Bonn for further studies and repair, which are still ongoing. The thin Silicon Nitrate window from Norcada with a thickness of 200nm does not yet survive the pressure difference we have hoped for, investigations with the company are ongoing to solve finally the problem. We are using at this moment instead a Mylar window of 2\textmu m, which would still result to a improved sensitivity compared to last year. As soon as the detector is repaired in Bonn, we will re-
install and resume data taking. As we had to use anyway one week for sun-filming (see below), therefore the reduced data taking time is effectively still negligible. Details are given in separate section of the report.

**Installation of the cavity**

The prototype cavity, which has a fixed frequency, was installed in one cold-bore of CAST in earlier summer after a tremendous effort for design, integration and production including a cold vacuum vessel, which contains the pre-amplifier station. The cavity was responding as foreseen after closing of the magnet, as well as in vacuum and at cold, while it survived a provoked magnet quench at 13kAmps. The same is true for the Hall-probes and the temperature sensors, which have been installed all around the cavity and the vessel. The next step will be to install a read-out system, which will be able to read constantly the response of the cavity. Details are given in separate section of the report.

**Schedule**

The baseline schedule, which was presented last June, has been since then fully respected. We had last week the scheduled sun-filming campaign which verifies that the magnet movement is fully aligned to the sun movements and awaiting now the InGrid detector back to resume solar Chameleon data taking up to the end of the year. After having the KWISP detector fully set-up to its sensitivity, we hope to give at the end of our data taking period still some days to the KWISP data taking. Then warming up of the magnet is expected toward Christmas. Next year as mentioned above, we will have another half of year the upgrade of the cryo-system, which we will use to install at least in one cold-bore more cavities with adjustable resonance frequency and further improvements to KWISP and InGrid, to start data taking at a similar time as this year. The final schedule for 2017 will depend on the outcome of each detector’s performance in 2016 and we will decide in January 2017.

2.2 **Sun filming**

Twice a year it is possible to check the precision of the magnet's pointing to the Sun with a direct method, by observing the Sun in the optical part of the electromagnetic spectrum. It consists in taking pictures by a commercial photo-camera with a telephoto zoom lens that is firmly attached to the magnet and precisely aligned to the V1 bore of the magnet with the help of surveyors before the actual start of the filming (https://edms.cern.ch/document/1548745). Once the optics is aligned, and obviously depending on the atmospheric conditions, a series of photos is taken during the Sun tracking. Since the Sun is at low angles the correction for the atmospheric refraction is applied that allows a precise tracking also in the optical part of the Sun's emission spectrum.

During the last year some minor improvements and refurbishments were done. There is a new dedicated PC for control of the setup and analysis. Otherwise the setup remained the same. The procedure remained the same with components always on in order to avoid possible perturbations in the system. In March 2016 Sun filming was not performed since the experiment was in the shutdown phase with the magnet at the room temperature. It was decided not to incline the magnet in order to avoid possible damage from the magnet movement since it was not clear at the time what are the mechanical tolerances at the room temperature. However, the magnet was cooled afterwards and the data taking was restarted so
a Sun filming is now in progress. The camera was aligned with the help of the surveyors, and the filming was starting. By today (23.09.2016) Sun was visible only one day and it was behind the clouds. The analysis is in progress.

In Fig. 2.1 a plot is shown with the results updated to September 2015. The magnet is always 4 mm ahead of the Sun. It has to be stressed that the results were obtained by different setups, different people analyzing the pictures and different surveyor teams performing the initial alignment.

Thus also in this campaign similar results are expected. Cause of this effect should be searched in a systematic effect that did not change during these years. Possible explanation could be in the errors that appeared in transfer of coordinate systems. This transfer occurred twice. First transfer of the coordinate system is from the magnet axis to the fiducial points on the magnet and the second is from outside of the hall to the inside. Although it is not probable that an error happened during the transfers also this will be investigated since an error in the tracking program is excluded during tests performed in previous years.

![Figure 2.1 Results from previous Sun filming campaigns.](image)

### 2.3 Data taking

The 2015 data taking campaign started on 19th of June and was completed on 20th of November. All the detectors were in operation: two Micromegas detectors mounted on the sunset side of both bores of the magnet, the novel Micromegas detector in the focal plane of the LLNL X-ray telescope on sunrise side of one magnet bore, and the InGrid detector in the focal plane of the MPE X-ray telescope on the other sunrise bore. During the 2015 data taking period, 289 solar trackings were covered out of possible 310 trackings, leading to the data taking efficiency of 93%.

The data taking program in 2016 started in April when the first data taking with the KWISP detector was performed. During the period 21st of April to 28th of April, 9000 s of tracking data and 121400 s of background data were recorded. The data taking with the InGrid detector started on 3rd of September. Two scheduled CERN interventions started on 12th of September and ended on September 16th. This period was used by the InGrid group to inspect a problem regarding a part of the detector.
3 InGrid Detector

For the 2016 run the detector underwent a major upgrade. The upgrade comprised several improvements:

3.1 Multi-Chip readout

It had been observed that many low energetic events were clustering in the corners and close to the rim of the InGrid. Therefore, we surrounded the central InGrid with 6 additional InGrids. The new module was equipped with 7 InGrids, the so-called Septemboard (see Fig. 3.1) and was successfully commissioned. To keep the electrical drift field as homogenous as possible close to the border of the detector an electric field cage was introduced, which works as designed.

![Image of the Septemboard (7-chip InGrid)](image)

**Fig. 3.1** Image of the Septemboard (7-chip InGrid)

The detector was operated in August and early September at the CAST experiment. There, some tracks could be successfully recorded. In Fig. 3.2 an example event is shown, a highly ionizing track passing over the top left and the rightmost InGrid barley passing over the corner of the central chip. The charge deposited on the central InGrid mimics a low energetic X-ray photon, but can be discarded because of the additional information of the surrounding InGrid. This demonstrates the additional background suppression potential of the new setup.
Fig. 3.2 Background event recorded by the upgraded 7-chip InGrid detector (upper 5 chips shown). A highly ionising track passing is seen crossing four of the seven chip. The hits left on the central chip alone are photon-like but can now be vetoed by the signature on the surrounding chips.

However, around the start of the run a short in one of the outer 6 InGrids developed and lead to a loss of HV at those grids. A constant current indicated a resistance between a grid and ground and discharges between the independently powered central grid and the outer grids could be observed. The detector was dismounted and brought back to Bonn on September 12th, taking advantage of 1-week power invention followed by a Sun filming campaign. No obvious damages could be observed when the detector was opened, except damages on the inactive sides of the grid, where the discharges were taking place. No vital parts of the grids were damaged, but only the inactive border.

After several studies a faulty grid could be isolated. The exchange of the grid is possible, but since several other grids don't seem to be in a good condition, the decision was taken to build a new Septemboard instead of repairing the first one. At the time of writing (28.9.), the new Septemboard is being tested at Bonn. After reassembly of the detector, data taking with the InGrid detector can be resumed.

3.2 Decoupling of grid signal

The decoupling of the analogue grid signal to be recorded along with the (digital) InGrid information has been implemented in the hardware and the readout chain. In the lab, it was demonstrated to work well with a single chip. During commissioning in the CAST environment, no useful grid data could be recorded yet since constant (non-destructive)
sparking (> 1 Hz) between the central grid and the surrounding grids prevented operation of the grid signal readout.

### 3.3 A large veto scintillator

A large scintillator read out by a PMT was mounted above the detector. A dedicated trigger was designed and works well. The information can be read out and combined with the other readout information. However, since the relevant information is the time between a signal on the grid (see 3.2) and the last veto scintillator signal, the system cannot yet be exploited in data taking.

### 3.4 Ultra-thin silicon nitride window

It was planned to replace the 2014/2015 cathode with a new cathode featuring a 200nm SiN opening. First prototype windows with a (too small) diameter of about 7 mm were delivered by the company early 2016 and showed a good performance. They withstood a pressure difference of about 1 bar. However, when the final, full-size samples were delivered, only pressure difference of 400-600 mbar could be reached before the windows burst.

![Fig. 3.3 Background event recorded by the upgraded 7-chip InGrid detector (upper 5 chips shown). A highly ionising track passing is seen crossing four of the seven chip. The hits left on the central chip alone are photon-like but can now be vetoed by the signature on the surrounding chips](image)

Intense studies in close collaboration with the supplier are ongoing to understand the reason for the failures. To date about 10 samples have been tested at Bonn without final conclusions. Additional 20 samples are still awaiting testing. At the time of writing, a 300 nm full-size sample passed 2 successive pumping cycles, however further reliability tests are needed before a safe operation in CAST can be envisaged.

It was studied whether the (too small) 7mm diameter 200nm thin SiN windows would perform better than 2 µm Mylar windows (as currently used) using simulation. The 2 µm Mylar window without an additional differential window (0.9 µm Mylar) showed a better performance than the small SiN windows. The 2 µm Mylar window now installed is gastight enough to allow for operation without differential window, but still reaching the vacuum level required for operating behind the XRT. No additional differential window is used anymore in the current setup.
3.5 Small veto scintillator

This project was deemed the least significant, since it influences only the high energetic (~8 keV) part of the spectrum and was postponed due to limited person power.

4 KWISP Detector

4.1 Initial on-beam installation and April 2016 solar tracking run

Following the preliminary results of the off-beam tests, a decision was made to initially install on beam a Michelson-type sensor setup, in order to be ready with a stable detector by the first available data taking window. In this setup, equivalent to a single-pass Fabry-Perot, the membrane (5x5 mm², 100 nm thickness) is placed at the end of one of the interferometer arms. This optical assembly was mounted inside the KWISP on-beam vacuum chamber operating in the 10⁻⁶ mbar range (see Fig. 4.1 and 4.2). The membrane was aligned in the focal plane of the MPE X-ray telescope at a 5-degree incidence angle with respect to the incoming solar chameleon beam (alignment was carried out by CERN surveyors). A chameleon chopper was also installed in front of the membrane to modulate in amplitude the chameleon beam, providing the necessary reference frequency and a trigger signal for data acquisition.

For the first ever solar run with a force sensor, a series of morning sun-tracking measurements was carried out from 21st to 28th April 2016, using the setup briefly discussed above. Data taking strategy consisted in recording, as a function of time, both the output of the interferometer, read by a photodiode, and the trigger signal from the chameleon chopper. Data were continuously acquired in 100 s long time records, both during sun-tracking, and during off pointing periods, providing background data. In 7 days of running 9000 s of sun-tracking data and 121400 s of background data were obtained. Data analysis consists basically in a frequency analysis of the interferometer output, searching for a possible peak at the chopper characteristic frequency. This peak would signal an excitation of the membrane carrying the signature of the chopped chameleon beam. Fig. 4.3 below shows a sample spectrum from a preliminary sun-tracking run. A full data analysis is in progress, while the sensor has been dismounted in order to carry out the necessary modifications as briefly discussed below.

![Image](https://example.com/image.png)

Fig. 4.1 The initial KWISP on-beam installation
Fig. 4.2 Input-output optics for the sensor of Figure 1

Measuring time = 100 s
Freq. resolution = 0.00625 Hz
Sensitivity = 1.35x10^{-17} N/Hz

Fig. 4.3 Sample spectrum of the sensor output during tracking (see text)
4.2 Modifications and upgrades

The KWISP Fabry-Perot cavity will be frequency-locked to the sensing laser beam using the Moving Mirror (MM) technique. To fully implement this scheme the 28 mW @1.064 nm, Nd:YAG Alphalas “Monopower” laser has been factory-upgraded to include a voltage-actuated external temperature control. This will allow for precise tuning over a range of several GHz and, eventually, automatic locking of the cavity. A new vacuum chamber for the on-beam setup has been designed (Trieste) and built (Freiburg) and is now ready for installation (see Fig. 4.4). An off-beam test station has also been setup and is available for measurements on different membrane and cavity configurations without affecting the running detector.

![Fig. 4.4 New KWISP on-beam vacuum chamber (see text)](image)

4.3 On-beam installation

In order to start as soon as possible with performance tests and noise measurements on the on-beam KWISP setup, the sensor will be installed initially on the CAST magnet at the side of the InGrid detectors, ready to be moved in the XRT focal plane for enhanced-flux data taking when scheduled. For this purpose, the KWISP on-beam chamber, already complete with vacuum-compatible remotely-controlled motion degrees of freedom for cavity mirrors and membrane (see Fig. 4.5), will be mounted on a monolithic (45cm)x(60cm) optical breadboard also supporting the laser and the necessary cavity injection optics. To provide passive vibration isolation the breadboard is resting on special "sorbothane" rubber feet. A pair of mating aluminum bars, with suitable receptacles, allows the breadboard to be placed in position on the CAST magnet (see sketch at left in Fig. 4.6). This arrangement also gives the possibility of setting up and aligning the optics off-beam, then transferring the breadboard directly in place on-beam. A schematic layout of the optical system to be mounted on the on-beam optical bench is shown in Fig. 4.6 at right. Once the initial installation and testing phase are carried out, the on-beam setup will be completed with an outer layer of special foam for acoustic insulation.
Fig. 4.5 Inside view of the KWISP vacuum chamber with remotely-controlled motion stages (see also text)

Fig. 4.6 – (left) Sketch of the on-beam assembly system; (right) optics layout for the on-beam optical bench.

4.4 New chameleon chopper

A new chameleon chopper has been built using optical flats and tested up to a chopping frequency of about 500 Hz, a factor more than 200 higher than the chopper used in the April 2016 data taking run. This new device is shown in Fig. 4.7.

Fig. 4.7 New chameleon chopper built using optical flats (see also text).
5 Status of the CAST-CAPP/IBS Detector

5.1 Overview

A major milestone for the CAST-CAPP Relic Detector project was reached during the past quarter, consisting in the installation of one working (not tunable) rectangular cavity inside one of the CAST magnet bores (Fig. 5.1). The cavity remained in stable working conditions after the magnet reached its lowest temperature and after a quench from full magnetic field.

A data acquisition system is in its procurement phase at the CAPP; a test using loaned equipment is expected during the second half of October.

Stable data taking is expected to start before the end of calendar year 2016. The cavity operating frequency will be \( \sim 6.08 \text{ GHz} \), corresponding to an axion mass of \( \sim 25.1 \text{ micro-eV} \). To have a reliable sensitivity estimate from axion detection, the cavity environment at low temperatures and high field needs to be fully understood. This can occur only after all equipment has been exported from Korea and the experiment fully commissioned.

The following observations should be taken into consideration: Crucial cavity tests could not be performed before CAST magnet ramping to full field, which occurred at the beginning of September 2016; Procurement of a data acquisition system requires additional CAPP budget from authorized expenditures during fiscal year 2016. These expenditures were authorized only during the second half of August, as part of a CAPP additional budget request. A plan for 2017 is sketched in the last part of this report.

5.2 January-May 2016

An intense preparation work involved all collaborating institutions. This work culminated with the assembly, commissioning and installation of one cavity inside one of the CAST magnet bores, on June 20th 2016. The work mainly included:

- The design and fabrication of cavities at different stages of design evolution
- The integration with the CAST magnet environment, including the design and fabrication of two vacuum vessels, i.e. the low-temperature electronics housing near the magnet bores, with associated cooling provisions to ensure cryo-electronics operation at or near the magnet operating temperature.
- The design and procurement of flanges with feedthroughs.
- The realization and procurement of temperature and magnetic field monitoring systems.
- The planning and procurement of a cabling and wiring system
- The design and procurement of a cavity anchoring system in the magnet.
- The evaluation and decision process regarding the safety of an installation for the CAST magnet integrity.
- Metrology of the CAST magnet bores.
5.3 June-September 2016: Integration with the CAST magnet

- All mechanical, cryogenic, and electrical integration aspects have been completed.
- Vacuum vessels:
  - Funded by CAPP, of CERN design and fabrication, following CAPP requirements.
  - Design, fabrication, testing and installation work completed.
  - Two vessels have been fabricated. One vessel was installed (Fig. 5.2).
- Flanges with hermetically sealed feedthroughs (Fig. 5.3).
  - Two flanges were realized at CAPP. Their function is to allow wiring of the cavity and low-temperature electronics from the high vacuum, low temperature of the magnet bore to room temperature.

- RF cavity installation
- Installation occurred on June 20th, 2016
- Magnet quenching issues.
  - A decision committee including magnet experts met on May 30th, 2016 and concluded that the cavity design and in-bore anchoring provisions were adequate for installation and safe operation.
- After a few design iterations one cavity was assembled, tested, and installed inside one bore (Fig. 5.4).
- The cavity resonant frequency at room temperature is 6.05 GHz (Fig. 5.5). Inside the magnet at low temperature the frequency is shifted up to ~ 6.08 GHz (Fig. 5.6).
- The cavity working conditions remained stable often the CAST magnet quenched from its full operating field, indicating that the project can move to data taking.
- The installed cavity is not tunable
- Further development: Short term
  - The procurement and commissioning of a data acquisition system. The integration of the acquisition system in a monitoring and networking system for the experiment.

5.4 CAPP Contribution (Capital + Travel)

- 2016: US$ 420,000
  - It should be noticed that ~ US$ 200,000 were invested, in capital, at CAPP in 2015 as preparation work during the phase of proposal development, until approval by the CERN SPSC.

5.5 Further developments: R&D

- Design and fabrication of longer rectangular cavities.
- Amplifiers in high magnetic fields.
  - Multi-cavity operation.
  - Cavity tuning and coupling for multi-cavity operation.

5.6 Plan for year 2017

Place and operate ten cavities inside the CAST magnet.
Each cavity will have a maximum outer length of 40 cm, fitting in a cylindrical envelope of 40 mm diameter. A cavity having this maximum size should fit inside both bores at any position along their length, as established by bore metrology results. If only one bore will be available, at least five cavities will be installed. Note: With ten cavities operating at the same frequency, a $10^{-14}$ GeV$^{-1}$ axion-to-photon coupling constant sensitivity can be reached in about one week of running, for an axion mass of 25 µeV (6 GHz). A cavity quality factor of 20,000 has been assumed for this estimate.

Fig. 5.1 Cavity insertion inside the CAST magnet bore

Fig. 5.2 Cavity insertion inside the CAST magnet bore
Fig. 5.3 The outer flange with feedthroughs.
**Fig. 5.4** Installed cavity

![Graph](image1)

**Fig. 5.5** The installed-cavity resonance before (lower frequency) and after the CAST magnet bore was pumped at room temperature

![Graph](image2)

**Fig. 5.6** The installed-cavity resonance at low temperatures, in full magnetic field.
6 RADES

RADES is an exploratory project to develop high-frequency RF cavities with good scaling-up properties, exploiting filter-like resonant structures, and complementary to the CAST-CAPP approach. During the last year, efforts have been focused on preliminary design and simulation work and optimization studies, while resources for a hardware test were being sought as part of a funding application to the Spanish MINECO. A first design of a small 5-pole filter cavity have been finalized and a first prototype is now under construction. Very recently, we have been notified of the approval of the funding application, and therefore the program towards the installation of a first RADES cavity in CAST is expected to be carried out in the near future.

7 Calibration of new XRT at PANTER

CAST’s multilayer X-ray telescope (operated in 2015 with the Sunrise Micromegas Detector) has been fully characterized at PANTER (MPE) with the goals to find the best focus position, measure the effective area of the telescope at a range of energies from 0 to 9 keV, define the spot size, point spread function and vignetting due to general off-axis obscuration.

7.1 Simulation

Previous to the measuring campaign at PANTER, the CAST team deployed a full simulation toolkit by means of ray-tracing to understand and predict the telescope response.

Because of finite source-to-optic distance, the best focus position should be an additional ~17 mm beyond the f=1500 mm focal length or $f_{\text{eff}}=1517\text{mm}$, where $D=130.297\text{ m}$. The ray-trace code auto-focus function finds a best-fit focal length at ~1519 mm.

$$\frac{1}{f_{\text{eff}}} = \frac{1}{f} - \frac{1}{D}$$

We’ve performed simulations for the point spread function and the spot size at best focus for different energies so that we can compare them directly to measured data for Al-K$_\alpha$ (1.4 keV), Ti-K$_\alpha$ (4.5 keV) and Fe-K$_\alpha$ (6.4 keV):
Fig. 7.1 This is an end-on view, looking directly into the entrance aperture of the optic. We have back-projected photons that have successfully reflected on the parabola (upper) and hyperbola (lower) mirror. Blue line is “bottom” of each shell, red line is “top” of each shell.

Some very interesting results from simulation show that for intra-focal imaging at higher-energies the outer-most shells start to cut-out as expected, such that if the distance between optic and detector were to be shortened in an experimental setup one should be able to observe the predicted variation in the response of different shells depending on the incident energy.

Fig. 7.2 Point spread function simulations for Al-K (left), Ti-K (center) and Fe-K (right).

7.2 PANTER Measurements

During July 2016, CAST transported its multilayer X-ray telescope from CERN to PANTER where the optic was taken out of its vacuum housing and coupled to the PANTER vacuum chamber via an aluminum interface. A first, visible-light alignment of the XRT was completed using a goniometer and a laser system.
The initial alignment was refined using incident X-rays at the Al-K energy followed by adjustments in pitch and yaw angles to maximize the flux through the telescope at the focal plane (see Fig. 7.5).

After the telescope was fully aligned, the effective area for different energies was measured at an extra-focal position to increase the measurement precision, in particular the following energies were used: C-K (0.277 keV), Cu-L (0.93 keV), Al-K (1.49 keV), W-M (1.775 keV), Ag-L (2.98 keV), Ti-K (4.51 keV), Cr-K (5.41 keV), Fe-K (6.4 keV), Cu-K (8.04 keV). Two examples of these measurements are shown in Fig 6.6. This procedure is standard efficiency calibrations of telescopes used both in space missions and ground experiments.
Throughput of the telescope for yaw (left) and pitch (right) tilting angles. Al-K photons were used to illuminate the telescope’s aperture.

Extra-focal images for C-K and Al-K calibrations at PANTER.

The effective area of the telescope was successfully characterized at PANTER and first, preliminary results are shown in Fig. 7.7, as well as vignetting for the yaw and pitch angles (Fig. 7.8).
Fig. 7.7 Measured effective area (red squares and cyan triangles) in comparison with ray-trace simulations (blue, yellow, green). In blue the simulated on-axis effective area is shown, while simulations of the scaled on-axis (orange) and off-axis effective area (green) are also included. The cyan dots are the on-axis measurements while in red the off-axis measurements at PANTER.

Fig. 7.8 Measured vignetting effects in pitch angle (left) and yaw angle (right)

In general, the PANTER data agreed very well with the simulations performed before the calibration campaign at MPE as it can be seen from the preliminary analysis of the point spread function data (see Fig. 7.9) and the intra-focal imaging performed at low and high energies (see Fig. 7.10). Detailed analysis of effective area, point spread function as well as intra-focal imaging is in progress and will published in a journal of high impact.
The measurement campaign of CAST’s multilayer XRT at PANTER was very successful. The simulation toolkit and the results obtained at PANTER agree. The focal length measured at PANTER was 1519 mm, which is what our ray-trace simulation predicted given the geometry of our setup. A preliminary effective area of the telescope has been obtained and off-axis performance of the XRT has been fully characterized. One of the most remarkable achievements it has been to lower the energy threshold of the multilayer XRT below the 1 keV mark. From the status of our analysis, the measured point spread function of telescope is in strong agreement with simulations, final analysis will be published in the near future.
8 Analysis of 2015 data

8.1 Status of Micromegas data analysis in the vacuum phase

The new vacuum phase in CAST encompasses the 2013, 2014 and 2015 data taking campaigns. During these years, the exposure and sensitivity of the experiment to axions with masses $m_a < 0.02$ has been remarkably increased, thanks to the use of improved detection systems with lower backgrounds. Namely, in 2012 we upgraded the passive and active shielding of sunset Micromegas detectors (SS1 and SS2), achieving the best background levels ever obtained in CAST. However, the most important upgrade in the detection system is the installation of a new telescope in the sunrise line for the 2014 and 2015 data-taking campaigns, with an improved low-background detector (SR) situated at its focal plane.

The SR line consists on a shielded Micromegas (MM) made from radiopure materials placed at the focal point of a ~5 cm diameter, 1.3 m focal-length, cone-approximation Wolter I x-ray telescope comprised of thermally-formed (or ”slumped”) glass substrates deposited with multilayer coatings. This technology for x-ray optics is the one used in NASA’s hard x-ray astrophysics NuSTAR satellite [1] and was identified in [2] to have the potential to cost-effectively cover the areas needed for IAXO with excellent performance.

In this sense, the combination of the telescope with a low-background detector is a pathfinder project of the IAXO experiment, providing an enhancement in the signal-to-background ratio. The Micromegas detector was also redesigned: a field shaper was installed to homogenize the drift field; the readout pattern was modified to improve its performance (reaching an energy resolution of 13% FWHM at 5.9 keV, close to the best values obtained with small non-pixelated microbulk prototypes); as the signal region is expected to be reduced to a $< 5$ mm spot, the x-ray window strongback pattern was modified to contain the expected axion signal image; a muon veto consisting on a 5 cm-thick plastic scintillator was also installed on top of the shielding. More details on the SR line can be found in [3].

The alignment and commissioning of the line was successfully carried out in September 2014. The effective imaging of the x-rays through the telescope is demonstrated by a set of dedicated measurements consisting on the emission of x-rays from the other side of the magnet and their detection in the MM detector, as shown in Fig. 7.1. However, the efficiency of the telescope has just been measured in July at PANTER facility, as described in the previous section and the analysis of these data is ongoing.

In 2013, only SSMM detectors were operative, while in 2014 and 2015 both the SSMM and SRMM detectors took data, the latter, placed at the focal plane of the new x-ray telescope, as described before. Since then, ~842 and ~290 hours of solar tracking data have been recorded by the SSMM and SRMM detectors respectively. The detailed breakdown in data sets is shown in Tables 1 and 2. We have performed the discrimination analysis of the Micromegas data, which allows us to determine the background level of the detectors and the number of events occurring during axion-sensitive conditions (i.e. solar tracking). The results of this analysis are shown in Table 1 and 2, for Sunset and Sunrise detectors respectively. The energy range of interest (RoI) is [2 – 7] keV, and the detector area is set to 14.5 cm$^2$ for the SS detectors, i.e. the cold-bore area. For the SR detector the energy RoI is the same, but the background is defined over a much smaller area (3.14 cm$^2$, the detector surface being daily calibrated). The background energy spectra of some data sets are shown in Fig. 8.2.
Fig. 8.1 Cool-X x-ray source illumination of the new x-ray telescope. Left: image measured by the Micromegas detector. Middle: simulation, assuming the Cool-X x-ray emission comes from a uniform 6 mm diameter spot. Contour levels are 6%, 30%, 50% and 80% of maximum intensity. Right: data of the Micromegas detector, now with the simulation contours over-plotted.

Fig. 8.2 Left: energy spectra measured during background (blue) and axion-sensitive conditions (solar tracking, in red) for SS2 Micromegas in 2014. The black line represents the expected axion spectrum for the upper value of $g_{\text{a}\gamma}$ excluded. Right: background energy spectrum before (blue) and after (red) the application of the veto cut in the SR 2015 detector.

<table>
<thead>
<tr>
<th>Year</th>
<th>Detector</th>
<th>Exposure [hours]</th>
<th>Level $[\times 10^{-6} \text{ keV}^{-1}\text{cm}^{-2}\text{s}^{-1}]$</th>
<th>$g_{\text{a}\gamma} \times 10^{-10} \text{ GeV}^{-1}$</th>
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<tbody>
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<td>2013</td>
<td>SS1</td>
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<td>0.81 ± 0.04</td>
<td>0.79 ± 0.18</td>
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<td>1409.2</td>
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Table 1: Summary of the data analysis with the Sunset Micromegas data. More information in the text.

The signal region on the SR detector is determined by detailed x-ray tracing of the telescope focusing effect (the point-spread function or PSF) on the set of incoming directions expected for the solar axion signal.
Table 2: Summary of the data analysis with the Sunrise Micromegas data. More information in the text.

(*) 3 candidate events, while 0.60 ± 0.13 are expected in the signal region and energy RoI.

The full integration of the PSF in the analysis is ongoing. A preliminary result is here presented using a rectangular signal region of 0.10 cm², shown in Fig. 8.3, that comprises 96.7% of the focused signal photons. The expected background in the signal region of the SR detector for the 290.2 hours of tracking data is of only 0.60 ± 0.13 events, while 3 candidate events are observed. The event hitmap of the solar tracking data of SRMM detector is shown in Fig. 8.3, with the 3 candidate events inside the signal regions. While this represents a mild excess over the background expectation, the combination of all vacuum data sets is statistically compatible with absence of signal. Therefore, a preliminary upper limit on the axion-photon coupling constant as a function of the mass is derived. The contribution of each data-set is shown in Fig. 8.4 and in the last column of table 1 and 2. From the combination of all the data sets we obtain preliminarily an upper limit to the axion-photon coupling constant of $g_{a\gamma} < 0.63 \times 10^{-10}$ GeV⁻¹ confidence level.

In the next months we will finalize the analysis including the efficiency and point-spread function (PSF) of the telescope, experimentally measured at PANTER, and we will study the possible systematics of the experiment.

This result will become the strongest and more solid upper limit on axion-photon coupling so far and a reference result from CAST in future. The relevance of the result is strengthened by the fact that it starts constraining the range of $g_{a\gamma}$ values hinted by the anomalous cooling rate observed in some stellar systems [4].

The preparation of a physics publication has started in the collaboration.

![Event hitmap of the solar tracking data of SRMM detector. Events identified as muons are in red, and candidate events are in blue. The four concentric rectangular extraction regions contain most of the axion flux: 72.7%, 88.8%, 96.7% and 99.6%. The area of these regions are respectively 3.12 mm², 5.80 mm², 10.08 mm².](image)
Fig. 8.4 Left: Preliminary exclusion curves at 95% C.L. in the $m_a$-$g_\gamma$ plane. Each data-set contribution is shown independently, as well as the combined result. Right: number of standard deviations from the null hypothesis.

References

8.2 Analysis of the 2014/2015 InGrid data

1. The search for solar chameleons using the InGrid data of 2014 and 2015 is approaching finalization. Few details, mainly concerning XRT parameters, have to be fixed before the analysis can be put forward to CAST analysis coordination to initiate the publication process.

Figure 8.5 shows the final observed spectrum in the energy range 0.2 keV – 2 keV. The data points are compatible with the background confirming the expected limit on $\beta_\gamma$ of $\sim 6.2 \times 10^{-9}$.
$10^{10}$ thus the potential to surpass the solar limit of $\beta_T = 6.457 \times 10^{10}$. The calculation of the observed limit will be performed once all parameters are final.

2.) Search for axions: A search for axions via the axion-electron coupling in an energy range of 0.2-10 keV was also started. The axion-electron coupling allows for Compton, bremsstrahlung, deexcitation and recombination production channels, thereby increasing the solar axion flux by about two orders of magnitude. The dependence of the axion detection on the Primakoff effect (axion-photon coupling) in the experiment only allows for a limit calculation on the product of the two coupling constants. The 2013 CAST CCD paper on axion-electron coupling derived a limit of $g_a g_{\gamma e} < 8.1 \times 10^{-23}$/GeV and it is being studied whether the InGrid can surpass this limit.