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## The x-ray telescope of CAST

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**Abstract.** The CERN Axion Solar Telescope (CAST) has been in operation and taking data since 2003. The main objective of the CAST experiment is to search for a hypothetical pseudoscalar boson, the axion, which might be produced in the core of the sun. The basic physics process CAST is based on is the time inverted Primakoff effect, by which an axion can be converted into a detectable photon in an external electromagnetic field. The resulting x-ray photons are expected to be thermally distributed between 1 and 7 keV. The most sensitive detector system of CAST is a pn-CCD detector combined with a Wolter I type x-ray mirror system. With the x-ray telescope of CAST a background reduction of more than 2 orders of magnitude is achieved, such that for the first time the axion photon coupling constant  $g_{a\gamma\gamma}$  can be probed beyond the best astrophysical constraints  $g_{a\gamma\gamma} < 1 \times 10^{-10} \text{ GeV}^{-1}$ .

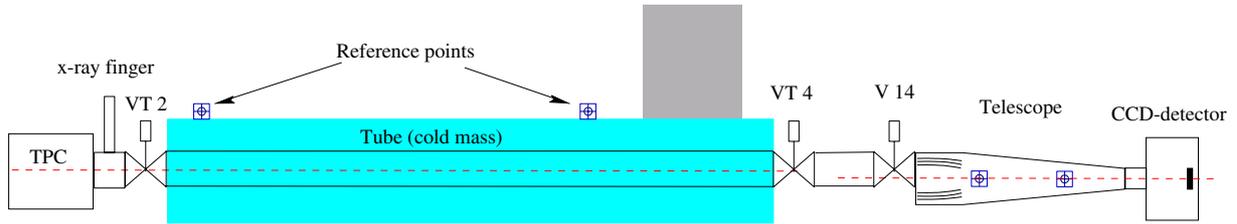
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## 1. Introduction

The CERN Axion Solar Telescope (CAST), searches for a pseudoscalar particle, the axion. The axion was motivated by theory as a solution of the strong CP problem<sup>14</sup> almost 30 years ago (Peccei and Quinn 1977, Weinberg 1978, Wilczek 1978). One of the most important properties of the axion is its coupling to two photons with a strength given by the coupling constant  $g_{a\gamma\gamma}$ . This coupling would allow the production of axions inside the sun via the Primakoff effect ( $\gamma\gamma \rightarrow a$ ) resulting in an axion flux proportional to  $g_{a\gamma\gamma}^2$ . The axion energy spectrum would be thermally distributed peaking at about 3 keV, reflecting the temperature distribution in the core of the sun (Sikivie 1983, van Bibber *et al* 1989, Andriamonje *et al* 2007b). In the presence of a transverse magnetic field  $B$  of length  $L$  solar axions convert to observable x-rays via the time reversed Primakoff effect with a probability  $P_{a \rightarrow \gamma} \propto g_{a\gamma\gamma}^2 (BL)^2$  within the limit of negligible momentum transfer  $q$ . In CAST we use a 9.26 m long superconducting dipole magnet with an

<sup>14</sup> Charge conjugation transformation followed by a parity transformation.



**Figure 1.** Schematic view of the experimental set-up of CAST. The TPC detector which observes the sun during sunset is shown on the left hand side. On the right-hand side the x-ray telescope system is shown. Please note that the Micromegas detector and the tracking system are not shown in this picture. The whole system is operated at a pressure of  $\approx 10^{-6}$  mbar.

acceptance region of  $14.5 \text{ cm}^2$  providing a 9 Tesla homogeneous transversal magnetic field to search for solar axions. The magnet is mounted on a movable platform which allows the track of the sun to be followed for about  $3 \text{ h day}^{-1}$ . On each end of the magnet background optimized x-ray detectors are installed, looking for photons from axion conversion inside the magnet tube. While the time projection chamber (TPC) (Autiero *et al* 2007) observes the sun during sunset, the x-ray telescope and the Micromegas detector (Giomatris *et al* 1996, Charpak *et al* 2002, Abbon *et al* 2007) are looking for axions during sunrise. Figure 1 shows a side view of the CAST magnet and the detector set-up. The Micromegas detector which is installed next to the x-ray telescope is not shown in this picture.

For given magnet parameters, the sensitivity of the experiment solely depends on counting statistics. The expected count rate from axion to photon conversion for the x-ray telescope of CAST in the energy range of 1 to 7 keV (spot region) is:

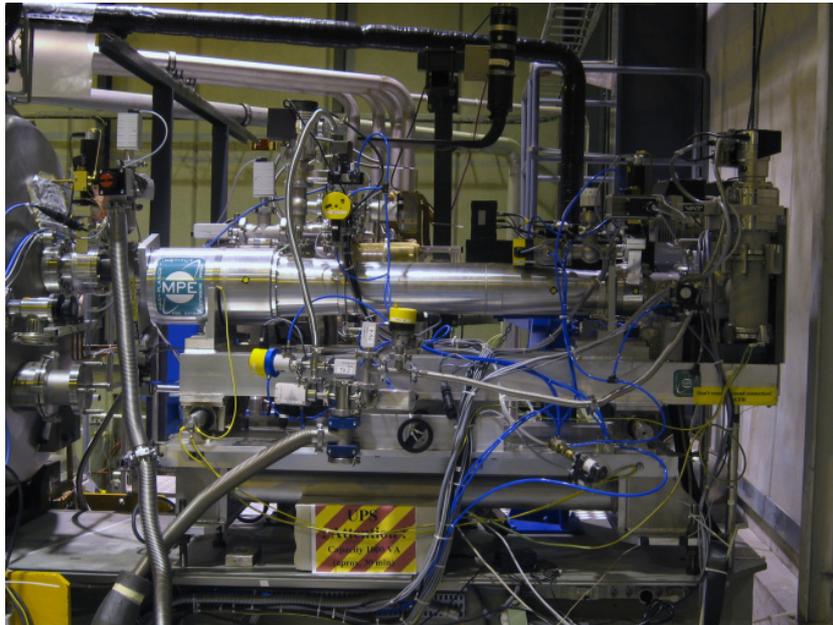
$$\Phi_\gamma \approx 1.81 g_{10}^4 \text{ counts day}^{-1} \quad (1)$$

including the effective area of the x-ray telescope system ( $g_{10} = g_{a\gamma\gamma} \times 10^{10} \text{ GeV}^{-1}$ ). Taking a mean observation time of the sun of  $1.5 \text{ h day}^{-1}$  into account, the expected signal count rate reduces to  $\approx 0.1 g_{10}^4 \text{ counts run}^{-1}$ . Thus as in other rare event experiments background reduction is indispensable to maximize the sensitivity of the experiment to detect a potential signal.

In this paper, we report on the performance, design, and shielding concept of the x-ray telescope. For a detailed introduction to the CAST experiment we refer the reader to Andriamonje *et al* (2007a). First results of CAST from the 2003 and 2004 data taking period were published by Zioutas *et al* (2005) and Andriamonje *et al* (2007b). The remainder of this paper is structured as follows: in section 2, we give a detailed description of the design of the x-ray mirror telescope of CAST including the pn-CCD (charge coupled device) detector, its calibration, and the alignment of the optical system relative to the magnet tube. In section 3, we present the long term performance of the system and systematic detector background studies. We summarize our paper in section 4.

## 2. The x-ray mirror telescope of CAST

Since the axion to photon conversion inside the magnet tube conserves the axion energy and momentum in first-order approximation, the resulting x-ray beam would leave the magnet bore

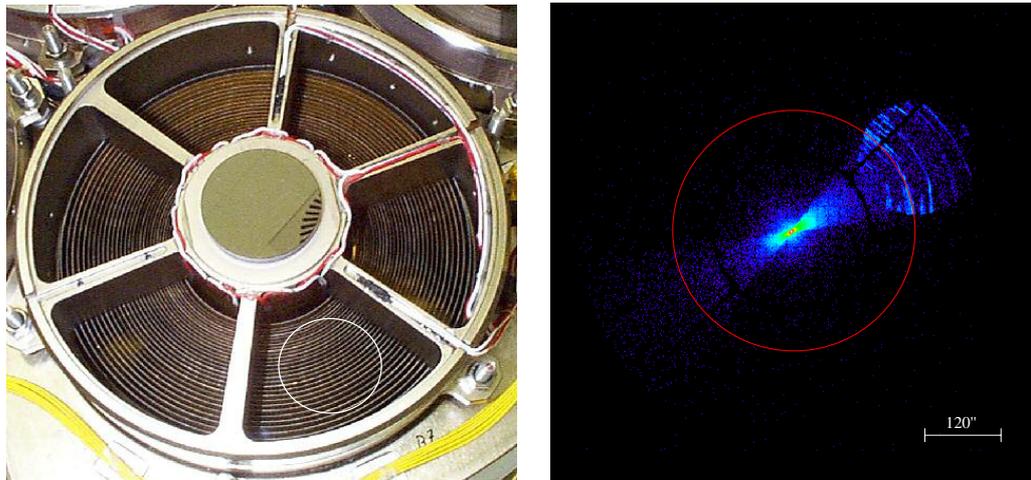


**Figure 2.** The x-ray telescope consisting of the Wolter I mirror system and a pn-CCD camera are mounted onto the superconducting magnet of CAST at CERN. The tube visible in the middle of the image houses the mirror module, the magnet bore is to the left, and the focal plane pn-CCD detector and its vacuum system is fixed to the mirror system to the right.

with a divergence given by the angular size of the axion producing region of the sun which extends from the centre of the sun to  $\approx 20\%$  of the solar radius. The resulting x-ray flux can then either be observed directly with a detector covering the magnet bore, as is the case for the Micromegas detector and the TPC of CAST, or it can be focused with x-ray optics onto a focal plane detector with a high spatial resolution. The advantage of the latter approach is twofold, additional background suppression by a factor of  $\approx 154$  due to the focusing of the potential signal from the magnet acceptance area of  $14.5 \text{ cm}^2$  to a small spot of  $\approx 9.4 \text{ mm}^2$ . Furthermore, due to the imaging capability an axion image of the sun could be acquired and systematic effects can be reduced by measuring the background and a potential signal simultaneously, taking into account the photon counts outside the area where the axion signal would be expected. The CAST x-ray telescope is based on the concept of a Wolter I mirror optics (Wolter 1952) which is a well-known technology used in x-ray astronomy (e.g. the Einstein, Exosat, Rosat, Chandra, and XMM-Newton x-ray observatories) and is a spare module which was originally built for the x-ray mission ABRIXAS (Altmann *et al* 1998, Egle *et al* 1998). The focal plane detector is a pn-CCD of the type that has been successfully used for more than 7 years for the European Space Agency (ESA) x-ray satellite XMM-Newton (Strüder *et al* 2001). The design and performance of the system will be described in the following sections.

### 2.1. The x-ray mirror system

The CAST x-ray mirror system (see figure 2) is a Wolter I type telescope consisting of 27 nested, gold coated, and con-focally arranged parabolic and hyperbolic nickel shells with a focal

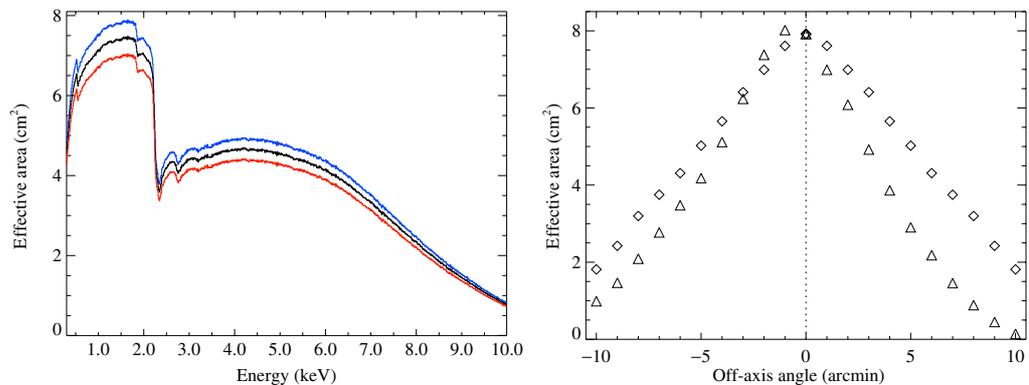


**Figure 3.** Left panel: front view of the mirror system. The individual mirror shells and the supporting spoke structure are shown. One of the six sectors is illuminated through the magnet bore, the approximate size of the magnet bore is indicated by the white circle. Right panel: logarithmic intensity image of a nearly parallel x-ray beam measured with one mirror sector at the PANTER test facility at an energy of 1.5 keV. For comparison, the red circle indicates the expected spot size of the solar axion signal. Due to the fact that the x-ray source is at a finite distance ( $d \approx 130$  m), photons reflected by only one of the parabolic or hyperbolic shaped surfaces are apparent in the image (circular shaped region towards the top right).

length of 1600 mm (Friedrich *et al* 1998). The maximum diameter of the outermost mirror shell is 163 mm while the smallest shell has a diameter of 76 mm. The individual mirror shells are nested in a spoke structure subdividing the mirror aperture into six azimuthal sectors (see left panel image of figure 3). Since the diameter of the bore of the CAST magnet ( $d = 43$  mm) is much smaller than the diameter of the outermost mirror shell, the telescope is mounted off-axis such that only one of the six mirror sectors is used for imaging (see figure 3, the projected size of the magnet bore is indicated by the white circle). For the application of CAST, the asymmetric illumination of the mirror aperture has the positive side effect that shadowing effects caused by the spoke structure do not occur in our set-up.

The overall performance of such an x-ray mirror system for a given focal length mainly depends on two parameters, the effective area and the spatial resolution, given by the point-spread function (PSF). In general, the effective area for a given mirror coating is a function of the off-axis angle, the micro-roughness of the mirror surfaces, and the photon energy. It decreases with increasing micro-roughness, photon incidence angles (lower reflectivity), and due to geometric effects (vignetting).

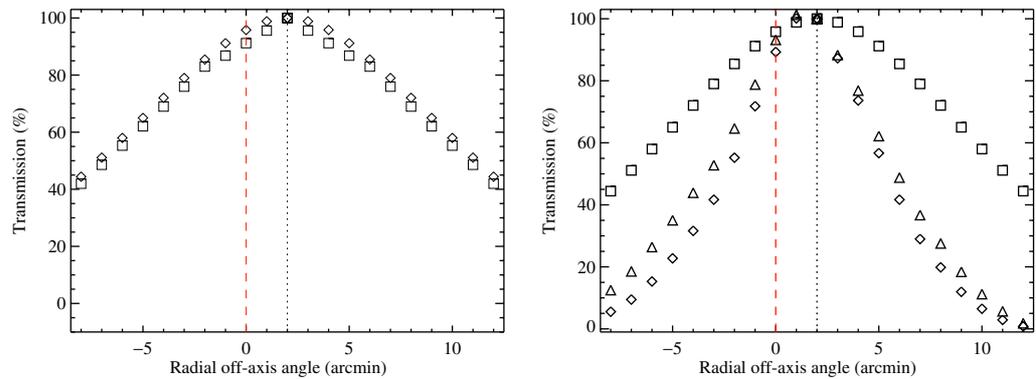
The effective area of the CAST mirror system has been predicted by means of ray-tracing simulations. The algorithm was developed for the ABRIXAS mirror system and has been adapted to the CAST set-up. For a given coating material, i.e. gold in our case, the ray-tracing simulations return the effective area and the PSF, both as a function of the photon energy and the off-axis angle. The micro-roughness of the mirror surfaces has been assumed to be 0.5 nm (rms) which is a typical value for the ABRIXAS mirrors. However, the influence of scattering effects due to the micro-roughness of the reflective surface are almost negligible.



**Figure 4.** Left panel: effective area of the x-ray telescope for a magnet bore aperture with a diameter of  $d = 43$  mm, given by the mirror reflectivity and the quantum efficiency of the pn-CCD. Three different cases are shown: the effective area of the mirror system for a point source for the data taking period of 2003 (blue line), the effective area for a point source located at an infinite distance for the data taking period of 2004 (black line), and for a source of the angular size of the axion emission region on the sun for the data taking period of 2004 (red line). Right panel: off-axis behaviour of the effective area of the mirror system only, for the data taking period of 2003 is shown for two cases: for radial off-axis angles (triangles) and tangential off-axis angles (diamonds). For a more detailed explanation see text.

More important for the actual imaging quality are the figure errors which influence the PSF and the reflectivity of the coating. Figure errors have not been included in the simulations but have been determined by x-ray measurements at the PANTER test facility of the Max-Planck-Institut für extraterrestrische Physik (MPE) (Freyberg *et al* 2005) using monoenergetic x-rays of different energies. The measurements, performed with full illumination of the mirror system, yield an on-axis angular resolution of the mirror system of 34.5 arcsec half energy width (HEW) at 1.5 keV and 44.9 arcsec at 8.0 keV, thus providing an oversampling of a factor of 10 in spatial resolution compared to the expected size of the ‘axion image’ of the sun. As an example the focal plane image of a point like source (distance  $\approx 130$  m) is shown in figure 3. The apparent asymmetry of the focal plane image originates from the asymmetric illumination of the mirror system.

In addition, the energy dependence of the effective area of the mirror system was measured over a series of distinct energies for each individual mirror sector. The sector with the best effective area was chosen for CAST. By combining the simulated effective area with the results of the calibration measurements, we calculated the on-axis effective area for the chosen sector and for the energy range important for CAST by interpolation (see left panel of figure 4). In figure 4 the effective area for the 2003 data taking period (blue line) is compared to the effective area for the 2004 data taking period (black and red line). For the 2004 data taking period the effective area is shown for two cases: the effective area for a point source located at infinity (black line) and for a realistic axion energy and intensity distribution of the extended solar axion source (red line). The overall combined efficiency of the mirror system and the pn-CCD detector for x-rays from axion conversion varies between 25 and 46% for the



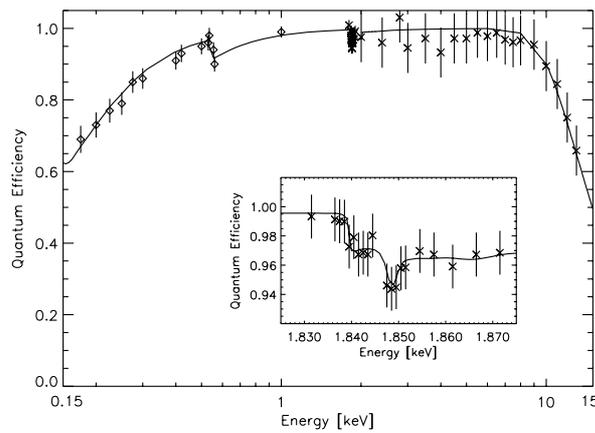
**Figure 5.** Left panel: vignetting losses due to the magnet bore geometry are shown for two cases: a point like source (diamonds) and an extended source of the angular size of the axion emission region on the sun (squares). Right panel: the transmission of the individual components (magnet bore, mirror system) depending on the off-axis angle. This includes the vignetting losses due to the magnet bore (squares), the radial off-axis transmission of the mirror module (triangles), and the total transmission of the whole system including both components (diamonds, a more detailed explanation is given in the text).

2004 detector set-up depending on the photon energy. In order to achieve a better centring of the solar axion spot on the CCD, we had to permanently tilt the telescope by  $\approx 2$  arcmin relative to the axis of the magnet during the data taking period of 2004. As a consequence the efficiency for the data taking period in 2004 is reduced compared to 2003. The right panel of figure 4 shows the simulated radial and tangential (relative to the mirror shell surface) dependence of the effective area. According to this picture, the tilt of the telescope results in a reduction of the effective area by  $\approx 10\%$  in absolute value. The radial off-axis behaviour shows a slight asymmetry due to the fact that only one sector of the mirror system is illuminated, which breaks the radial symmetry of the mirror system.

In order to estimate geometric effects due to magnet bore and the influence of the finite size of the axion source, we included the magnet tube geometry and the shape of the axion emission region on the sun in our simulations. To simplify matters the beam pipe was assumed to be a perfectly straight tube with a diameter of 43 mm. The right image of figure 5 shows the combined transmission for an extended source depending on the off-axis angle for the 2004 data taking period. The maximum transmission is offset from off-axis angle 0 due to the fact that the x-ray telescope optical axis is slightly tilted relative to the optical axis of the magnet bore, as mentioned before.

## 2.2. The pn-CCD detector

The focal plane detector of the CAST telescope is a  $280 \mu\text{m}$  thick, fully depleted pn-CCD. For a detailed description on the functional principle and an overview on the general characteristics and concept of this kind of detector we refer the reader to Strüder *et al* (1990) or Strüder *et al* (2001). The major advantages of such a device are the thick depletion region and its very thin (20 nm) and uniform radiation entrance window on the backside of the chip which results in a quantum efficiency  $\gtrsim 95\%$  in the entire photon energy range of interest (1–7 keV)

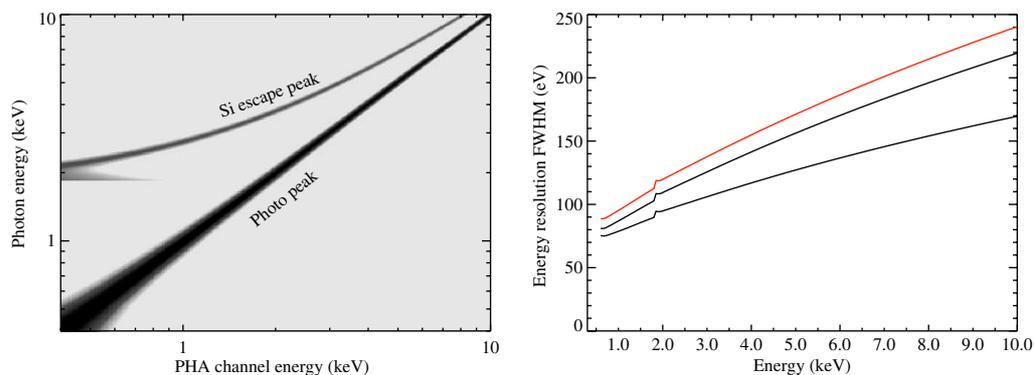


**Figure 6.** Left panel: quantum efficiency (QE) of the fully depleted pn-CCD as measured for the EPIC pn-camera of XMM-Newton (Strüder *et al* 2001). The drop of the QE at 0.53 keV is due to absorption losses in the SiO<sub>2</sub> passivation layer at the detector surface. The inset shows the absorption fine structure close to the Si-K edge at 1.84 keV. The solid line represents a detector model fit to the measurements. Right panel: the focal plane pn-CCD detector inside the CAST telescope. The gold plated cooling mask surrounding the rectangular pn-CCD chip (black part in the centre) is connected to a cold finger of a Stirling cooler on the top of the detector chamber via flexible copper leads. Electrical connections to the printed circuit board behind the CCD chip are provided via the flex-lead leaving the chamber on the bottom. The internal Cu/Pb shield is removed in this picture.

for the solar axion search. The left panel of figure 6 shows the quantum efficiency measured for a similar device, the pn-CCD on board of the European x-ray observatory XMM-Newton (Strüder *et al* 2001).

The pn-CCD has a sensitive area of 2.88 cm<sup>2</sup> divided into 200 × 64 pixels with a size of 150 × 150 μm<sup>2</sup> each. This corresponds to an angular resolution of 19.3 × 19.3 arcsec<sup>2</sup> given the focal length of 1600 mm for the x-ray optics. The 64 columns of 200 pixels are read out in 6.1 m in parallel followed by an integration period of 65.7 m resulting in a total cycle time of 71.8 m. Since the pn-CCD is operated continuously, it is sensitive to photons all the time and the detector has no dead time. Although for photons registered during read out, the pixel coordinate in the shift direction cannot be determined. This results in a fraction of ‘out-of-time’ events of 8.1% assuming a circular intensity distribution with a diameter of 23 pixels ≈ 3.45 mm (corresponds to 82.6% encircled axion flux) for the expected solar axion image. The pn-CCD provides a larger sensitive area than the expected ‘axion image’ of the sun.

The operating temperature of the CAST pn-CCD is −130 °C and is kept stable with a Stirling cooler system. The thermal coupling between the cooling system and the pn-CCD is provided by flexible copper leads connecting the cold finger of the Stirling cooler with the cooling mask of the pn-CCD chip (see right panel of figure 6). The detector is housed inside an aluminium



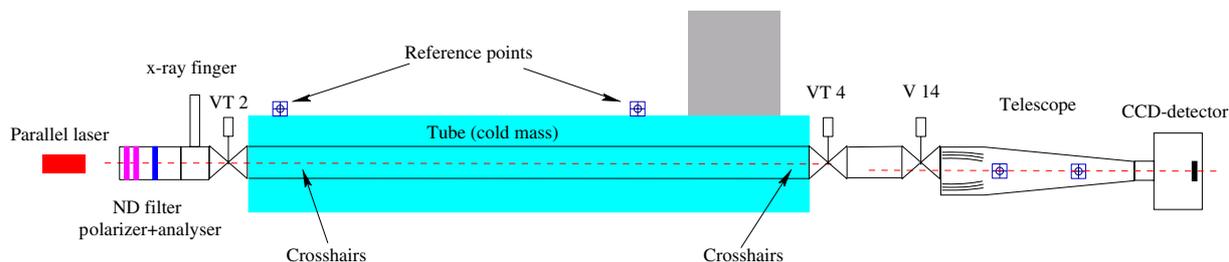
**Figure 7.** Left: detector response matrix of the pn-CCD detector. Apparent are the contributions of the photo peak and the Si-K $\alpha$  escape photons. The width of the distribution corresponds to the finite energy resolution of the detector. The colour scale is logarithmic. Right: energy resolution of the CAST pn-CCD and the EPIC-pn detector of XMM-Newton depending on the incident photon energy and different pattern types. From top to bottom: the combined energy resolution of the CAST pn-CCD for single and double event patterns (see text for a more detailed explanation), the energy resolution of the EPIC pn-CCD for double events, and for single events only. The XMM-Newton EPIC pn-CCD data is taken from Popp *et al* (2000) and Haberl *et al* (2002).

vacuum vessel with a passive shield (removed in figure 6) of typically 10 mm of oxygen free Cu and more than 20 mm of low activity Pb almost free of  $^{210}\text{Pb}$  to reduce the environmental  $\gamma$ -ray background. An additional lead shield on the rear side of the detector reduces the  $\gamma$  background from the concrete wall of the experimental hall and thus reduces temporal changes of the background spectrum and level during magnet movement when the distance between the detector and the wall of the experimental area changes (Kuster *et al* 2005).

Using a multi-target x-ray tube we calibrated the pn-CCD detector *in situ* at CERN. From this data we derived the energy calibration and the detector redistribution matrix shown in the left part of figure 7, which in combination with the effective area describes the mathematical relation between the incident binned differential photon spectrum and the observed binned pulse height spectrum measured by the detector following the relation:

$$N_i = \sum_j R_{ij} \epsilon(E_j) S(E_j) (\Delta E)_j. \quad (2)$$

Here  $N_i$  denotes the number of counts per unit time interval observed in the energy bin corresponding to the photon energy  $E_j$ ,  $\epsilon(E_j)$  the effective area in  $\text{cm}^2$ ,  $S(E_j)$  the binned differential source spectrum in units of  $\text{counts cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$ ,  $(\Delta E)_j$  the finite energy width of the  $j$ th energy bin, and  $R_{ij}$  the redistribution matrix. The redistribution function includes the contributions from the photo peak, the Si escape peak which is expected at an energy of 1.74 keV below the photo peak, and the finite energy resolution of the detector. Second-order effects, like e.g. the influence of partial events, were not taken into account for the modelling of the detector response function. We consider these effects of minor importance for CAST, although they are



**Figure 8.** Schematic view of the experimental set-up of CAST for the alignment of the optical axis of the x-ray telescope to the magnet tube axis.

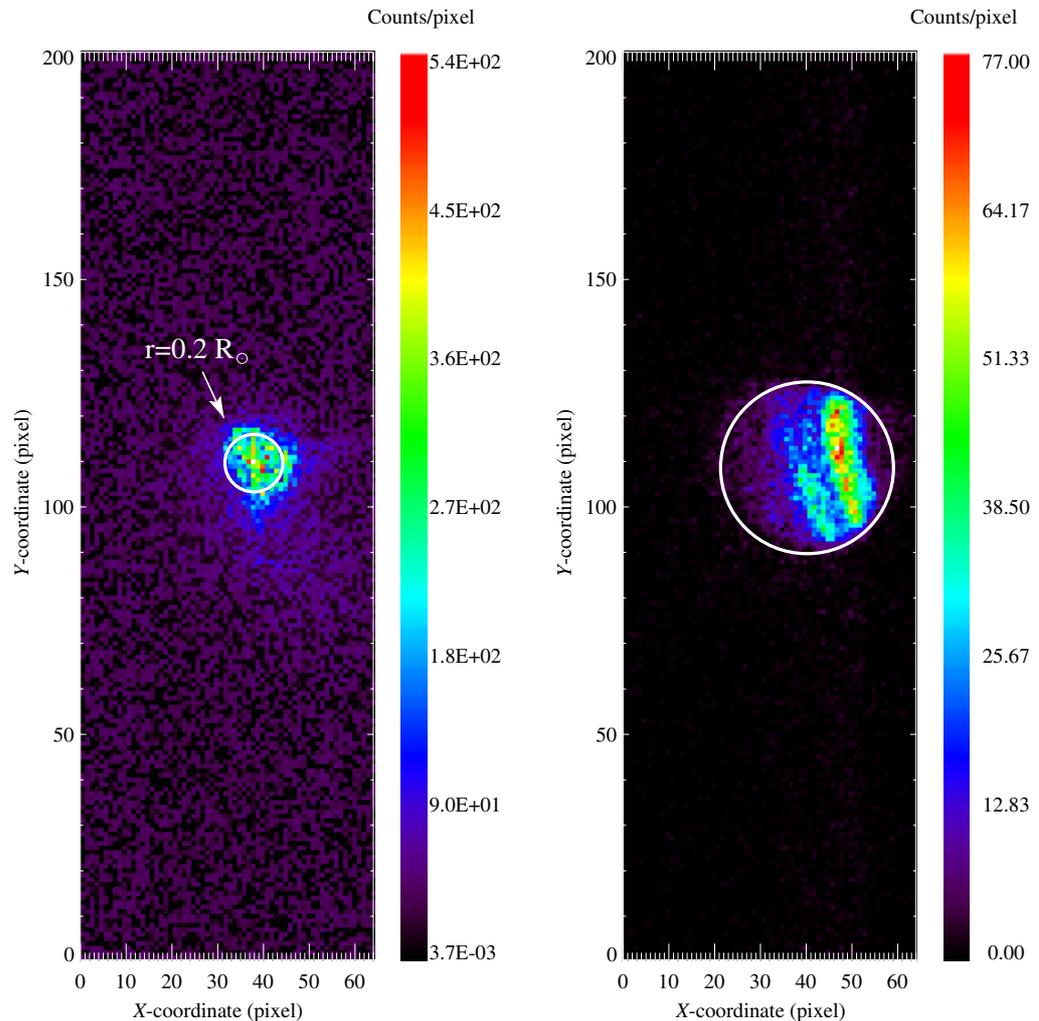
not negligible for high resolution x-ray spectroscopy (see Kahn and Blissett 1980, Popp *et al* 2000 for a detailed discussion).

Furthermore, we extended the calibration to energies which were not reachable with the x-ray tube ( $E > 9$  keV) using x-ray fluorescent lines apparent from the observed background spectrum (see section 3.1 figure 12). Together with an  $^{55}\text{Fe}$  calibration source, these lines also provide a valuable tool to monitor the long term stability of the energy calibration. By fitting a sixth-order polynomial to these calibration data, we derived the incident photon energy to detector channel conversion for the energy range from 0.5 up to 10 keV. The energy resolution of the pn-CCD detector shown in figure 7 depends on the energy of the incident photon and on the pattern type of the registered event, i.e. whether the charge cloud generated by the incident photon was registered in one, two, three, or four pixels (single, double, triple, and quadruple event patterns). Single and double event patterns contribute in the energy range of 1–7 keV with a fraction of 83 and 16.3% to the total number of observed pattern types. The remaining fraction of 0.7% are triple and quadruple patterns. To characterize the energy resolution depending on the incident photon energy for the CAST pn-CCD we adopted the detector response model which is actually in use for XMM-Newton EPIC pn-CCD underlying the same physical detector parameters. Figure 7 shows the resulting energy resolution of the XMM-Newton EPIC pn-CCD for single and double event patterns separately, and the resulting energy resolution of the CAST CCD detector. To model the energy resolution of the CAST detector we combined the noise contributions of single and double event patterns. As apparent from figure 7, the energy resolution of the CAST detector is slightly worse compared to the energy resolution of the EPIC pn-CCD.

### 2.3. Telescope alignment and pointing accuracy

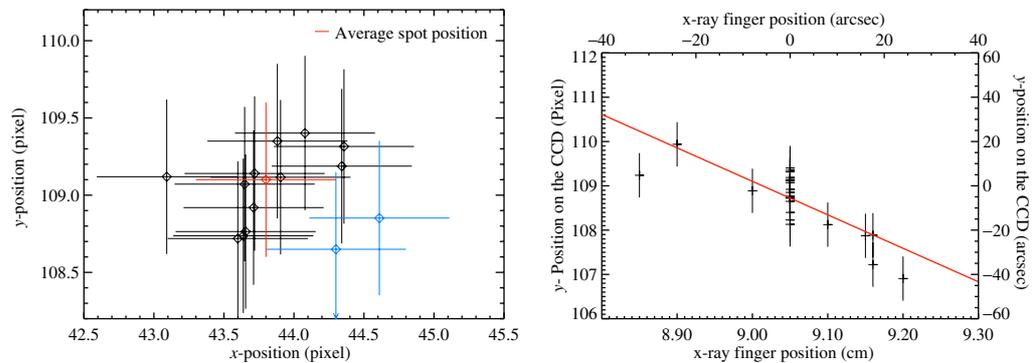
In order to achieve maximum performance of the x-ray mirror system, the optical axis of the x-ray telescope was aligned to be parallel with the magnet axis to an angle better than 40 arcsec using a laser system providing a parallel beam, shining through the entire system. For the duration of the alignment measurements the laser system is installed on the opposite end of the magnet instead of the TPC detector. The CCD detector can be replaced by a focusing screen, which allows the focal image produced by the parallel laser beam to be observed. An overview of the experimental set-up during the optical alignment is shown in figure 8.

To be able to monitor the stability of the alignment and the location of the potential axion image on the CCD detector, for the data taking periods in 2004, a  $\approx 70$  MBq pyroelectric x-ray source emitting mainly 8 keV photons was installed on the optical axis of the system, in front of the TPC detector. The device labeled ‘x-ray finger’ in figure 8 can be moved in and out of



**Figure 9.** Left panel: the focal plane intensity distribution of the parallel laser beam, defining the location where an axion signal would be expected. For comparison the size of the axion image of the sun is indicated by a circle with a radius of  $\approx 0.2R_{\odot}$ . Right panel: the focal plane intensity distribution of the 8 keV x-ray photons emitted by the pyroelectric x-ray source. The circle marks the size of the magnet bore projected onto the focal plane of the mirror system. The position of the laser spot (centre of the circle in the image on the left-hand side) has to coincide with the centre of this circle.

the field-of-view of the x-ray telescope. The major advantage of such a device compared to a radioactive source is that it can be turned off and consequently affects neither the background level of the TPC nor of the x-ray telescope. Since the source is located at a finite distance to the mirror system, the 8 keV photons of the source are focused 30 cm behind the CCD. Therefore, the observable x-ray image is larger than the focal spot of a parallel x-ray or laser beam as shown in the right panel of figure 9. The observed intensity distribution in the focal spot is not uniform since the emission strength depending on the angle of the x-ray finger is non-uniform and thus the focal plane image represents the emission characteristics of the x-ray finger. The potential



**Figure 10.** Left panel: observed location of the x-ray spot on the CCD for different magnet orientations. The x- and y-position of the x-ray spot on the CCD at the beginning of the data taking period in 2004 (black) and at the end of the data taking period in 2004 (blue) for different magnet orientations is shown. The red cross marks the position averaged over all measurements. Right panel: linear correlation between transverse x-ray finger position and the x-ray spot location as observed with the pn-CCD detector.

axion signal is supposed to be located in the centre of the circular envelope of the x-ray spot distribution. After the x-ray finger is aligned, the position of the x-ray spot can be used to monitor the stability of the alignment of the x-ray optics and to define the location of the potential axion image of the sun. The position of the laser spot relative to the x-ray spot provides an additional consistency check. The size of the focal spot of the parallel laser filling the magnet aperture should be well within the expected solar axion spot.

To verify the stability of the alignment, we observed the x-ray spot at the beginning and towards the end of the data taking period in 2004, during magnet movement, and for different magnet orientations. The barycentre of energy of the x-ray spot calculated from each measurement is shown in figure 10 before and after the 2004 data taking period, and during magnet movement. The measurements yield a stability of the position of the spot better than  $20 \text{ arcsec} \approx 1 \text{ pixel}$  throughout the data taking period of 2004. The overall pointing accuracy of the CAST helioscope inferred from redundant angular encoder systems and direct optical observations of the sun is better than  $\approx 1 \text{ arcmin}$ , which is perfectly adequate, given the angular field of view of the magnet bore of  $16 \text{ arcmin}$ . Since the x-ray finger was installed in 2004 after the first data taking period in 2003, the alignment could not be continuously monitored during that time. As a consequence we had to consider a larger and conservatively chosen extraction region for the potential axion signal on the CCD for the analysis of the 2003 data (Zioutas *et al* 2005). The results of an off-axis scan, demonstrating the linear correlation of the horizontal position of the x-ray finger and the location of the observed x-ray spot image on the CCD is shown in figure 10.

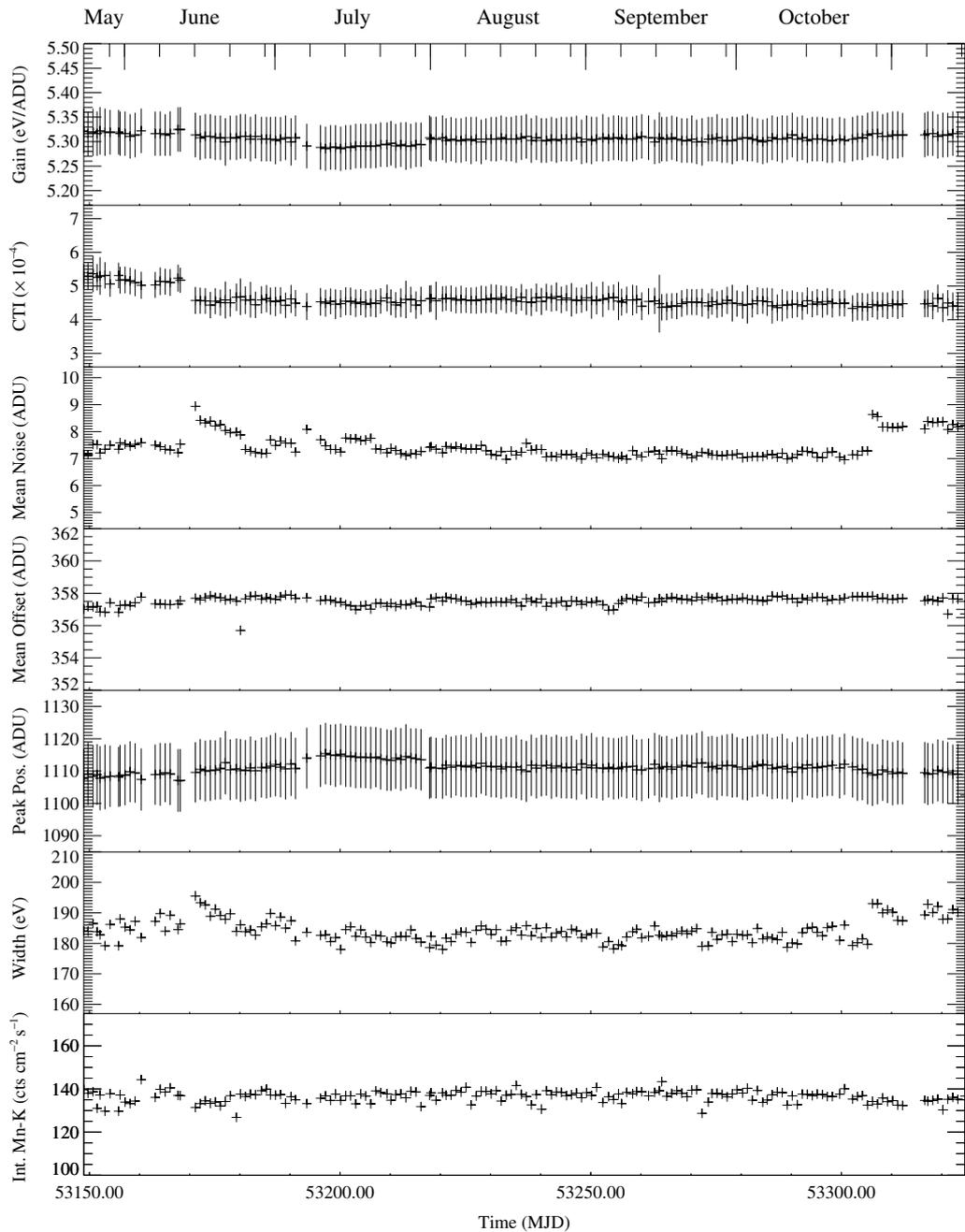
### 3. X-ray telescope performance

#### 3.1. Long term performance

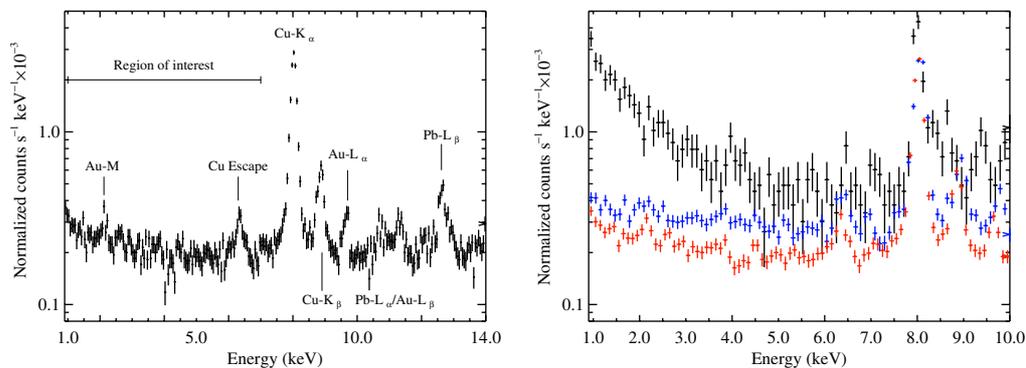
A valuable feature of the pn-CCD with integrated front-end readout electronics is the excellent longterm stability of operating parameters and performance resulting in homogeneous data sets collected over longer periods of time. Daily calibration measurements with the CAST pn-CCD using a flat field illuminating  $^{55}\text{Fe}$  source, allow permanent monitoring of the performance of the detector. A summary of the most important detector parameters monitored during the 2004 data taking period is given in figure 11. Please note that the errors indicated for the gain, charge transfer inefficiency (CTI), and peak position are dominated by the error of the fitting procedure. The signal noise averaged over all pixels shows variations which are correlated to variations observed in the energy resolution of the detector. Please note that both parameters do not mirror the performance achieved under controlled laboratory conditions. We assign this to the variable and sometimes high noise level in the CAST hall which was not designed to be a low noise experimental area. In no way did the observed degradation affect the result of the axion search, especially the overall detection sensitivity for axions of the experiment. All other detector parameters are stable throughout the data taking period of 2004, similar to the performance achieved during the 2003 data taking period of CAST.

#### 3.2. Detector background

In rare event searches which are not free of background, the background count rate limits the overall sensitivity of the experiment and background reduction becomes crucial to maximize the sensitivity of the experiment. In general, the detector background can be reduced by a choice of radio-pure detector materials, passive or active shielding of the detector, by pattern recognition methods, and by minimizing the active detector volume by focusing the expected signal to a small area on the detector. The fact that the CAST experiment is located above surface, and does not benefit from the shielding effect of the over burden of underground laboratories, limits the attainable background level. The strategy to maximize the signal-to-noise level of the x-ray telescope is therefore twofold: concentrate the potential axion signal on a small area of the detector and reduce the background by passive shielding as much as possible. A typical background spectrum measured during the data acquisition phase in 2004 integrated over the whole CCD sensitive area which demonstrates the performance of the x-ray telescope is shown in figure 12. In the axion sensitive energy range from 1 to 7 keV the resulting mean normalized count rate integrated over the full detector area is  $(2.21 \pm 0.02) \times 10^{-4}$  counts  $\text{s}^{-1}$   $\text{keV}^{-1}$ , corresponding to a mean differential flux of  $(8.00 \pm 0.07) \times 10^{-5}$  counts  $\text{cm}^{-2}$   $\text{s}^{-1}$   $\text{keV}^{-1}$ . The integral background count rate of 0.16 counts  $\text{hour}^{-1}$  in the solar axion spot area (9.4  $\text{mm}^2$ ) is remarkably low for an experiment above surface. The most prominent contributions to the low energy background apparent from figure 12 are the fluorescent emission lines from material close to the pn-CCD chip, like Cu (K-photo peaks and escape peak), Au, and Pb. Below 7 keV the background is dominated, besides the Si escape peak from the Cu line, by an almost flat continuum of predominantly Compton scattered photons and secondary electrons (for a more detailed explanation see Popp *et al* (1999) and Haberl *et al* (2002)).



**Figure 11.** Performance of the pn-CCD of the CAST telescope during the data taking period of 2004. The results are from daily calibration measurements using an  $^{55}\text{Fe}$  source. From top to bottom are shown: the gain of the detector (i.e. analog digital units (ADU) to eV conversion), the CTI, the mean noise and offset averaged over all 12800 pixels, the peak position, the width (FWHM), and the intensity of the Mn-K $\alpha$  line. The time is given in universal time (UT) as ‘modified julian day’ (MJD), i.e.  $\text{MJD} = \text{JD} - 2400000.5$  where JD is the julian day.

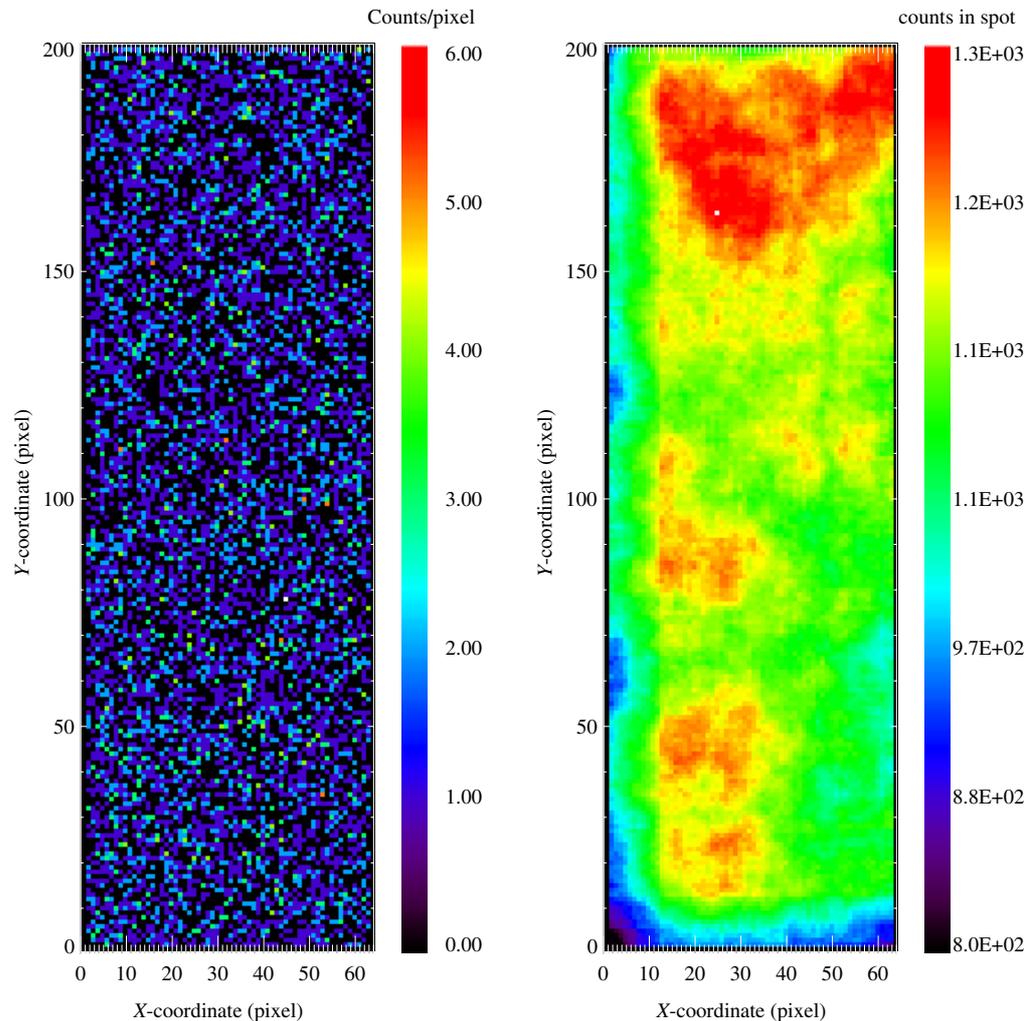


**Figure 12.** Left panel: background spectrum observed during non-tracking times, i.e. while the CAST magnet was not pointing to the sun but under the same operating conditions as during observations of the sun (see Andriamonje *et al* 2007b). The fluorescent emission lines apparent in the spectrum are labelled. The energy range which is sensitive for axion detection is marked as *region of interest*. Right panel: background spectra observed with the pn-CCD under different shielding conditions. From top to bottom: background observed with the internal copper shield (black) and with the internal lead and copper shield (blue). The lowest spectrum (red) represents the observed background with the final shield configuration, which consists (from the outside to the inside) of an external lead shield followed by the evacuated detector vessel, and the internal lead and copper shield.

The material close to the CCD chip had not been selected for low levels of radioactive impurities. Nevertheless, samples of all detector components close to the CCD chip and the pn-CCD chip itself were probed for their radioactivity in the Canfranc Underground Laboratory of the University of Zaragoza. Based on these activity measurements, simulations using the GEANT4 Monte Carlo simulation package were carried out to estimate the contribution of natural radioactivity to the overall pn-CCD background. According to the results of the simulations the contribution of natural radioactivity, e.g. induced by contamination of the detector materials with  $^{238}\text{U}$ ,  $^{235}\text{U}$ , or  $^{40}\text{K}$  can account for at most  $\lesssim 33\%$  of the observed background level, whereas about  $\approx 50\%$  of the measured background are induced by external  $\gamma$ -rays originating from the environment surrounding the detector (Cebrián *et al* 2007).  $^{222}\text{Rn}$  with a half-life of 3.82 days is usually one of the strongest sources of natural radioactivity and contributes significantly to the observed background (Heusser 1995). For the pn-CCD which is operated in vacuum the contribution of radon to the total background is not of importance at the actual level of sensitivity.

### 3.3. Background systematics

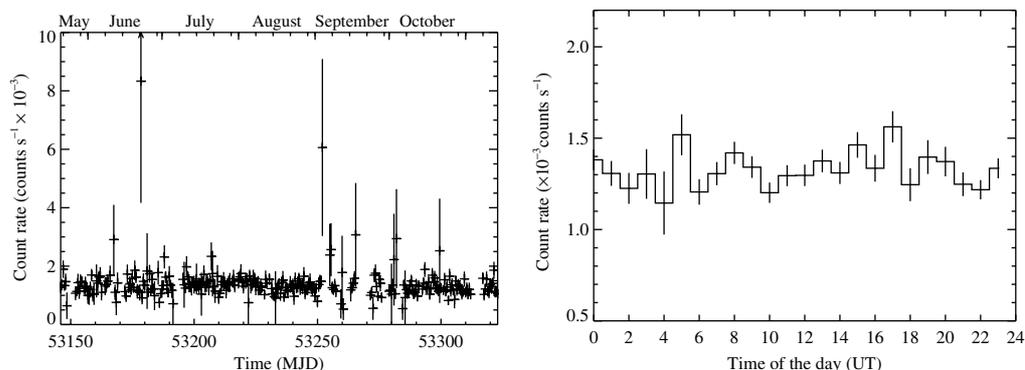
A major advantage of the x-ray telescope is the fact that the expected solar axion image is smaller than the active area of the pn-CCD and thus background and potential signal can be measured simultaneously during the observation of the sun by selecting different regions of interest on the pn-CCD. Nevertheless, we made extensive systematic studies of the observed background during tracking and non-tracking times and depending on different operating conditions. Figure 13 shows the spatial distribution of the events observed with the pn-CCD during 2004. The data were observed under axion sensitive conditions, but while the CAST



**Figure 13.** Left panel: background spatial distribution as observed by the CAST x-ray telescope during the 2004 data taking period. The intensity is given in counts per pixel and integrated over the full observation period of  $t_{\text{obs}} = 6805$  ksec. Right panel: the same data smoothed with a circular spot of the size of the expected axion image of the sun.

magnet was not pointing to the sun. Figure 14 shows the corresponding background light curve (count rate versus time), integrated over the sensitive area of the pn-CCD. The count rate stays constant at a level of  $(1.32 \pm 0.04) \times 10^{-3}$  counts  $s^{-1}$  over the entire data taking period of 2004 in the energy band of 1 to 7 keV. We also considered the variability of the background on different time scales. The right image of figure 14 demonstrates the temporal behaviour of the background count rate during one day, averaged over different magnet orientations. Selecting different extraction regions on the CCD does not affect the results we obtained for the spectral distribution and the temporal behaviour of the background.

A statistical analysis of the background count rate measured in 2004 while the telescope was pointing at the sun reveals a gradual decrease with time to a level of about 80% of the rate observed at the beginning of the 2004 data acquisition. Such a temporal behaviour could be due



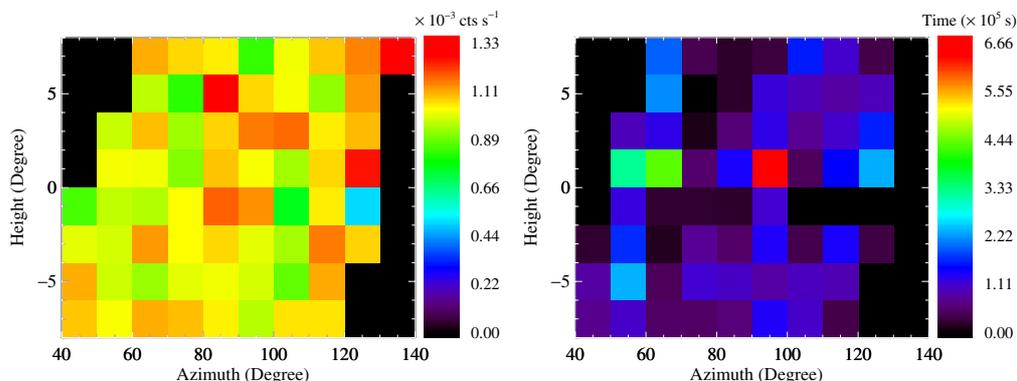
**Figure 14.** Left panel: time dependence of the background in the CAST axion sensitive energy range from 1 to 7 keV observed during the data taking period of 2004. The time is given as MJD (UT). Right panel: temporal behaviour of the background during the course of one day in the energy range from 1 to 7 keV.

to the systematical change of the detector location while following the solar azimuth at sunrise for a period of 176 days. The detector moves progressively away from the concrete wall of the experimental hall which according to MC simulation results could be a significant background source. During the 4 months data acquisition period in 2003 when the detector shielding was less hermetic and the background rate was higher by a factor of 1.5, no such change of background rate was observed.

During solar observations the CAST magnet and the detectors change their orientation relative to the environment of the experimental area (concrete walls, cryogenic installation). This movement might influence the background observed by the detectors in a systematic way. Especially the distance between the CCD detector and the concrete wall close to the CCD detector changes during individual solar observations. In addition, during the movement of the magnet, while following the track of the sun, the back side of the detector will face different areas of the wall which change during the course of the year. Measurements of the environmental  $\gamma$  background in the CAST experimental area with a germanium  $\gamma$  spectrometer show a variation of the contribution of, e.g. the  $^{238}\text{U}$  chain to the total environmental background by more than one order of magnitude between different locations in the experimental area (Dumont 2004). To minimize the influence of this effect on the detector background of the CCD, a lead shield was installed behind the CCD detector to reduce the apparent background variations below the limit of sensitivity of the CCD detector. Figure 15 shows the background count rate integrated over the full sensitive area of the CCD depending on the pointing direction of the magnet as observed with the x-ray telescope in the axion sensitive energy range (left image) and the corresponding integration time for each cell (right image). The residual variations apparent from the picture are within the statistical uncertainties consistent with a constant background level, taking especially the short integration time in some cells into account.

#### 4. Conclusions and outlook

The x-ray telescope of CAST has been in operation since summer 2003 and has been taking data in routine operation. First results of data acquired in 2003 and 2004 have already been published in Andriamonje *et al* (2007b) and Zioutas *et al* (2005). These results demonstrate how the sensitivity



**Figure 15.** Left panel: count rate observed with the x-ray telescope depending on the pointing direction of the magnet. Each cell has a dimension of  $10 \times 2^\circ$ . The attitude of the x-ray telescope is given in topocentric horizontal coordinates. Right panel: integration time for each cell.

of rare event experiments such as CAST can be improved by a combination of a focusing optics and a detector with high spatial resolution. Taking into account that an upper limit on  $g_{a\gamma\gamma}$  depends on the background count rate according to  $g_{a\gamma\gamma} \propto b^{1/8}$  (assuming Poissonian statistics), the x-ray telescope improves the sensitivity of CAST by a factor of  $\approx 2$ , compared to a non-focusing detector system. Further background reduction could be achieved by rebuilding the detector components from materials selected for radio-purity and with a graded-Z shield close to the pn-CCD chip which acts as an absorber for low energy photons ( $E < 7$  keV).

During 2003 and 2004 CAST explored the axion mass region up to  $m_a \lesssim 0.02$  eV. In the absence of a significant axion signal above background an upper limit on the axion to photon coupling of  $g_{a\gamma\gamma} < 8.8 \times 10^{-11}$  GeV $^{-1}$  (95% confidence level) could be derived. This new limit supersedes the previous astrophysical limits for axion masses  $m_a < 0.02$  eV from the helium-burning lifetime of horizontal branch (HB) stars (Raffelt *et al* 2006, 1996). The results from this data taking period were published in Zioutas *et al* (2005) and Andriamonje *et al* (2007b). Since mid 2006 the CAST experiment has been probing for axions with a mass  $m_a > 0.02$  eV (second phase of CAST). To explore this mass range the axion conversion region has to be filled with a buffer gas to restore coherence between the axion and photon wavefunction. By systematically changing the pressure inside the magnet bore the mass range from 0.02 to 0.8 eV can be covered. Due to the vast amount of pressure settings (approximately 660) necessary to scan the axion mass region continuously, the integration time per pressure setting (axion mass) is limited to 1.5 h per detector. As a consequence we expect  $\approx 0.20$  counts run $^{-1}$  (1.5 hours integration period) as background contribution. Further optimization of the shielding or detector materials would not significantly improve the sensitivity of the x-ray telescope of CAST.

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