An InGrid based Detector for the CAST Experiment

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Outline

1. Axions & the CERN Axion Solar Telescope
2. An InGrid based Detector for CAST – Why?
3. Integrated Micromegas – InGrid
4. Results of a Prototype Detector
5. Detector Integration
6. Conclusion & Outlook

Axions

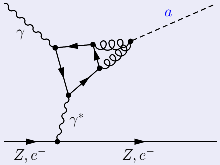
What are Axions? & Where do they come from?

- Goldstone-Boson arising from Peccei-Quinn mechanism
- PQ mechanism is elegant solution for the strong CP problem
  - Non-observation of CP violation in strong interaction
  - Smallness of electric dipole moment of neutron ($d < 0.29 \times 10^{-25}\, e\,\mathrm{cm}$)
- Candidate for parts of **Cold Dark Matter**

Coupling to ordinary matter

- Very small coupling constants
- Coupling to gluons realized in all axion models
- Mixing with π^0 leads to coupling to two photons

Primakoff effect



CERN Axion Solar Telescope

Axions from the sun

- Primakoff effect generates huge axion flux from the sun
- Axions can reconvert to photons inside large $\vec{B}$ fields
- Energy of solar axions below $15\,\mathrm{keV}$ (flux peaks at $3\,\mathrm{keV}$)

Current X-ray Detectors

- Microbulk Micromegas
- X-ray Telescope plus pnCCD

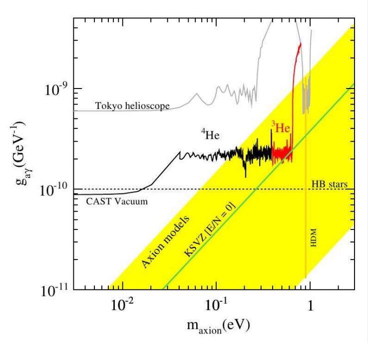
CAST – An axion helioscope

CAST – Data taking

- Magnet can track sun $2 \times 1.5\,\mathrm{h}$ per day
- Otherwise: background data
- Twice per year alignment can be checked visually

CAST – Results

Exclusion plot



PRL-107-26-1302(2011)

Exclusion limit

- No axions found up to now
- ^{4}He and ^{3}He used as buffer gas to restore sensitivity for higher axion masses
- CAST could set the most stringent limit for solar axions

An InGrid based Detector for CAST – Why?

Why a new CAST detector is needed

- Replacement of pnCCD will be necessary eventually
- Planned search for Chameleons (**Dark Energy** particle candidate) requires low threshold X-ray detectors ($< 1\,\mathrm{keV}$)

Benefits of a Micromegas with pixelized readout

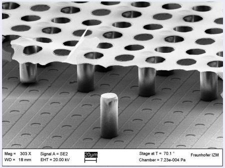
- Detection/Resolution of single electrons possible
- High spatial resolution can be exploited for event shape analysis (may be used for background rejection)
- Low threshold should be possible: about $300\,\mathrm{eV}$ (10 electrons)
- Purely digital data output due to integrated electronics

Integrated Micromegas – InGrid

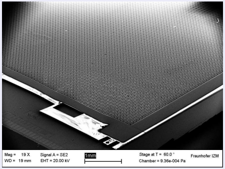
Micromegas on top of Timepix ASIC

- Fabrication by means of photolitho-graphic postprocessing
- Very good alignment of grid and pixels
- Each avalanche is collected on one pixel
- Detection of single electrons possible

InGrid - SEM



Timepix + InGrid



Production of InGrids

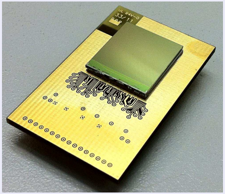
- Single and few chip processing: NIKHEF / Mesa+ (Twente)
- Wafer processing (~ 100 chips at once): in cooperation with IZM Berlin

Timepix ASIC

Facts about the Timepix ASIC

- 256×256 pixels, $55 \times 55\,\mu\mathrm{m}^2$ pitch
- $1.4 \times 1.4\,\mathrm{cm}^2$ active area
- Charge sensitive amplifier and discriminator in each pixel, $90\,e$ ENC
- Two modes: **Charge** or **Time**

Carrier board

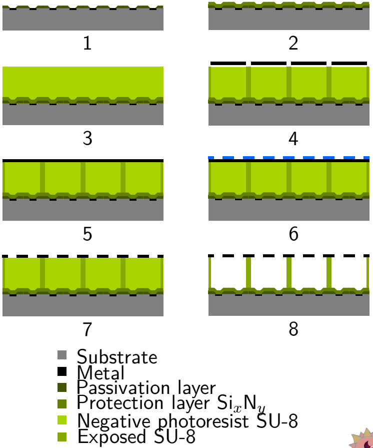


Protection of electronics

- Timepix ASIC is designed for imaging as readout electronics to be bump bonded on a silicon sensor
- Bump bond pads can be used as charge collecting anodes but electronics not designed to survive discharges
- Need resistive protection layer (e.g. 2-$8\,\mu\mathrm{m}$ silicon nitride) to spread charge in case of discharge

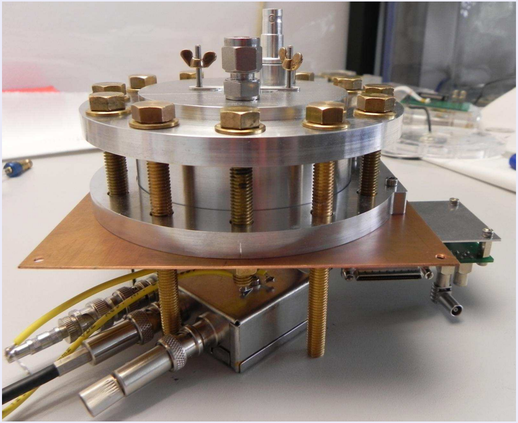
How to build an InGrid on top of a Timepix?

1. Starting with bare Timepix
2. Deposition of protection layer ($8\,\mu m$ Si_xN_y)
3. Deposition of negative photoresist SU-8 ($50\,\mu m$)
4. Exposure of SU-8
5. Sputtering aluminium ($1\,\mu m$)
6. Putting mask on aluminium layer (photoresist)
7. Structuring aluminum layer by etching the holes
8. Development of SU-8, cleaning of interistitials

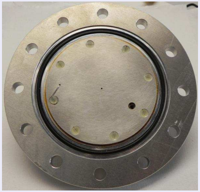


Prototype Detector

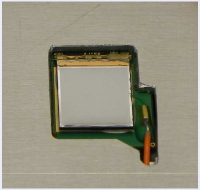
X-ray detector



Cathode

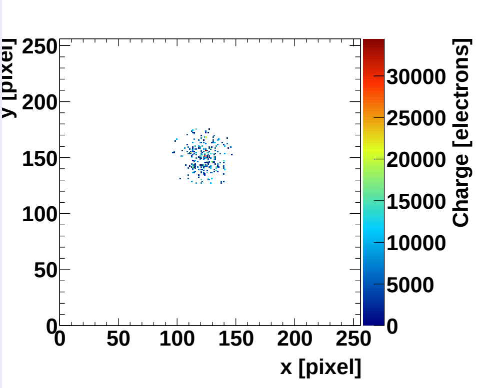


Anode

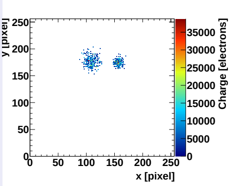


Typical X-ray Events

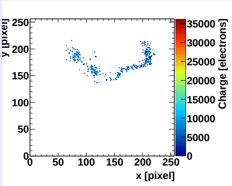
X-ray event



Double event

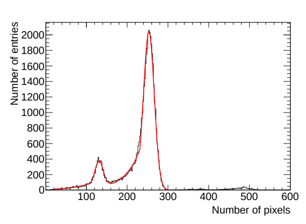


Background event

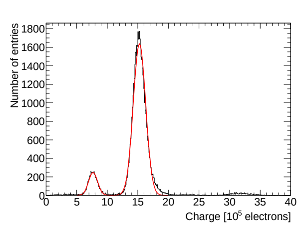


Detector Performance – Tests with ^{55}Fe

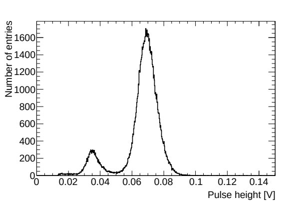
Spectrum - Pixels



Spectrum - Charge



Spectrum - Grid

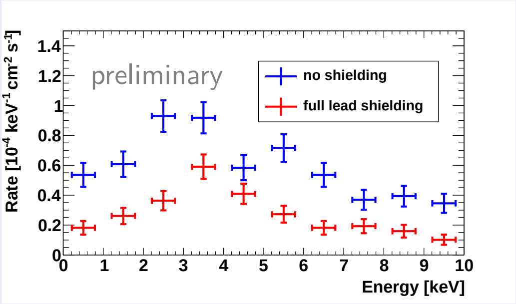


Energy resolution

- Ar/iC_4H_{10} 95/5
- Cr foil to suppress $6.1\,\mathrm{keV}$
- Pixels: $\sigma_N/N \approx 5.2\,\%$
- Charge: $\sigma_Q/Q \approx 6.7\,\%$
- Grid: $\sigma_U/U \approx 8\,\%$

Background Rates

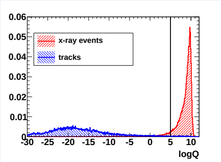
After Likelihood-Ratio based discrimination



- Reduction should be possible by improvement of algorithm

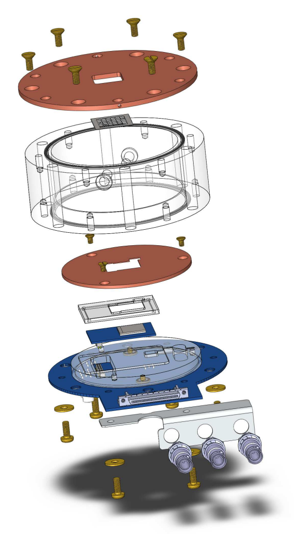
Lead shielding

Likelihood-Ratio



A CAST compatible Detector Design

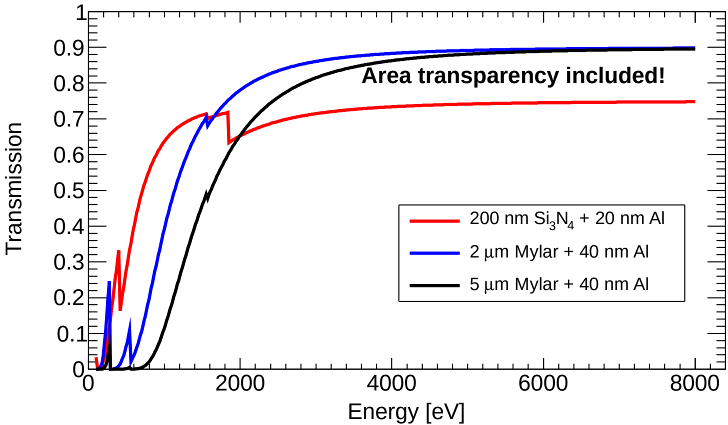
Exploded view



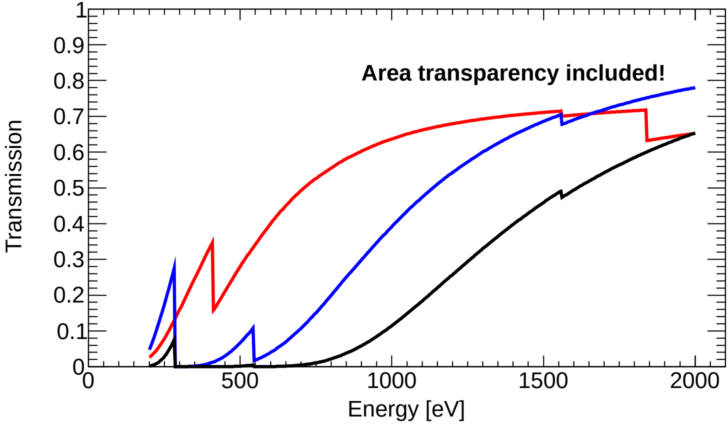
Features

- Modular design based on the current CAST Micromegas
- Body made of plexiglas
- X-ray windows:
    - Mylar films $2\,\mu m$ or $5\,\mu m$ with strongback
    - Under investigation: Array of silicon nitride membranes ($200\,\mathrm{nm}$ thick)
- Operation pressure: $1.1\,\mathrm{bar(a)}$ or higher

Comparison of X-ray Window Transmission

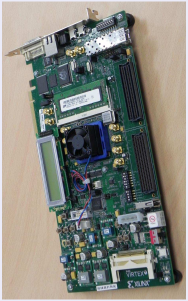


Comparison of X-ray Window Transmission



Readout System

Virtex6 board



FPGA based readout system

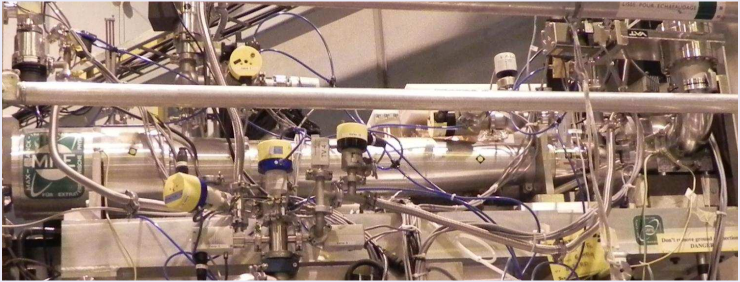
- A new readout system for Timepix ASIC is being developed at Bonn ($\rightarrow$ T77.1)
- FPGA based and therefore very flexible and adoptable to custom needs
- For CAST a slightly modified firmware will be used in combination with a Virtex6 evaluation board

Implementing the grid signal in the readout

- Idea: Use grid signal as kind of trigger
- Close Timepix frame few μs after trigger signal
- Maybe recorded grid signal and longitudinal event shape can be used for background discrimination

X-ray Telescope – Status Quo

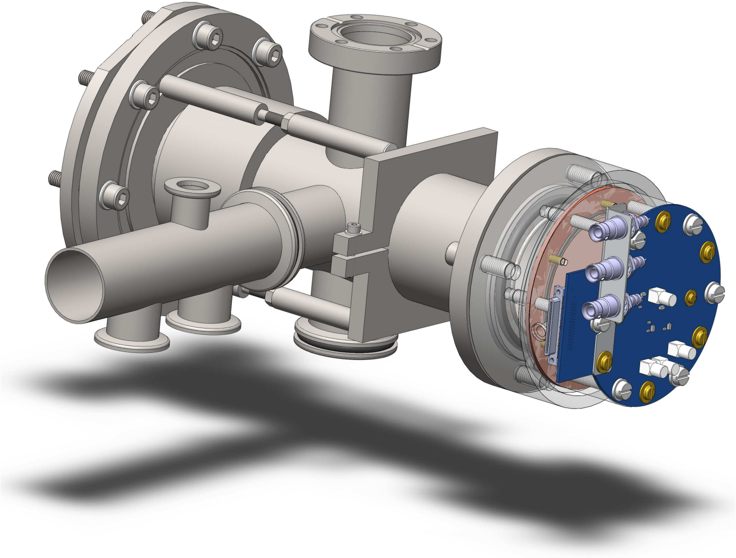
X-ray Telescope & pnCCD



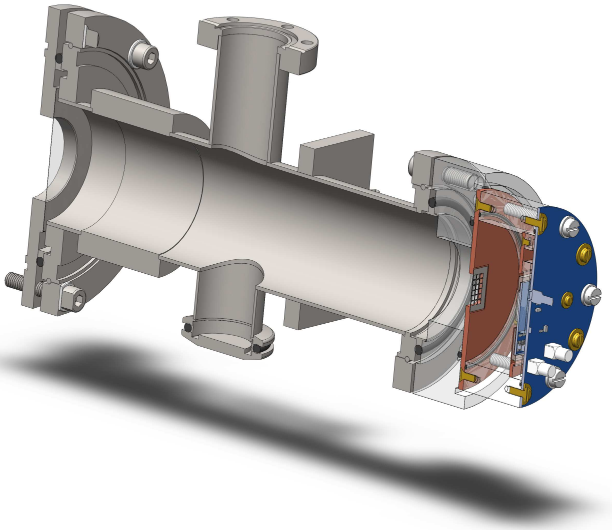
Interfacing the InGrid Detector with the XRT

- Very limited space: $\sim 300\,\mathrm{mm}$ from adopter to focal plane
- Need space for lead shielding and ^{55}Fe source manipulator
- Differential pumping may be necessary to ensure good vacuum in XRT

Interfacing the InGrid Detector with the XRT



Interfacing the InGrid Detector with the XRT



Conclusion & Outlook

Conclusion

- InGrid based X-ray detector has shown good energy resolution and promising background rates
- A CAST compatible detector based on InGrid technology has been designed (and built)
- Efforts to mount detector on XRT at CAST are ongoing

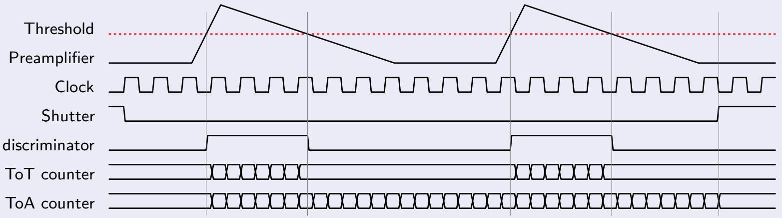
Outlook

- Tests at low X-ray energies in the CAST Detector Lab towards mid/end of April
- Installation of detector at CAST mid of the year
- Implementation of grid signal in readout scheme and improvement of background discrimination

Backup Slides

Timepix ASIC – More Details

Timing Diagram



Timepix 3

- Is under development and will be submitted this year
- Will be able to recognize multihits and to measure Charge and Time simultaneously
- Will allow data driven readout

The Peccei-Quinn Mechanism

Strong CP problem

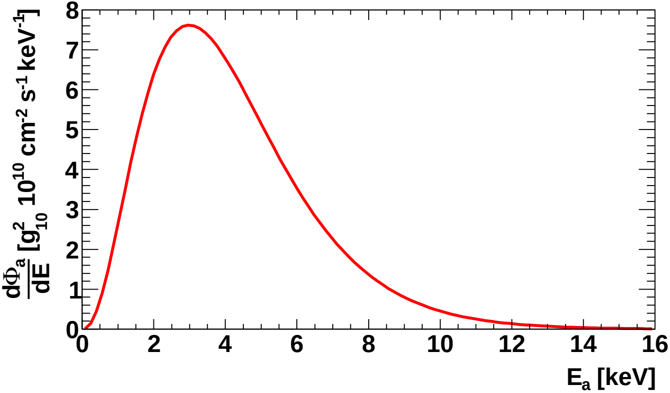
- Lagrangian of strong interaction contains CP violating term

$$\mathcal{L} = \underbrace{\sum_n \bar{q}_n(\gamma^\mu i D_\mu - m_n)q_n - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a}_{\mathcal{L}_{\text{QCD}}} + \theta\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

An elegant solution – The Peccei-Quinn mechanism

- A bit similar to Higgs mechanism
- Introduction of new global, chiral symmetry $U(1)_{\text{PQ}}$ which is spontaneously broken at energy scale f_a
- θ becomes dynamic variable instead of theory parameter
- Spontaneous symmetry breaking gives rise to a Goldstone boson called **axion**

Solar Axion Flux



Chameleons – Dark Energy Particles?

Dark energy as a new form of matter

- Scalar fields interacting with matter and photons could be strong candidates
- Constraints would lead to large gravitational effects and a fifth force with long range
- Exploit screening mechanisms to avoid unnatural models
- Chameleon screening: Models with a density dependent effective mass

Solar Chameleons

- Chameleons could be produced in the sun a bit similar to axions via a Primakoff-like effect
- Production not in the suns core but in a small shell around the tachocline and an energy spectrum peaking below $1\,\mathrm{keV}$