Prospects of
Hard X-ray polarimetry
with Astrosat-CZTI

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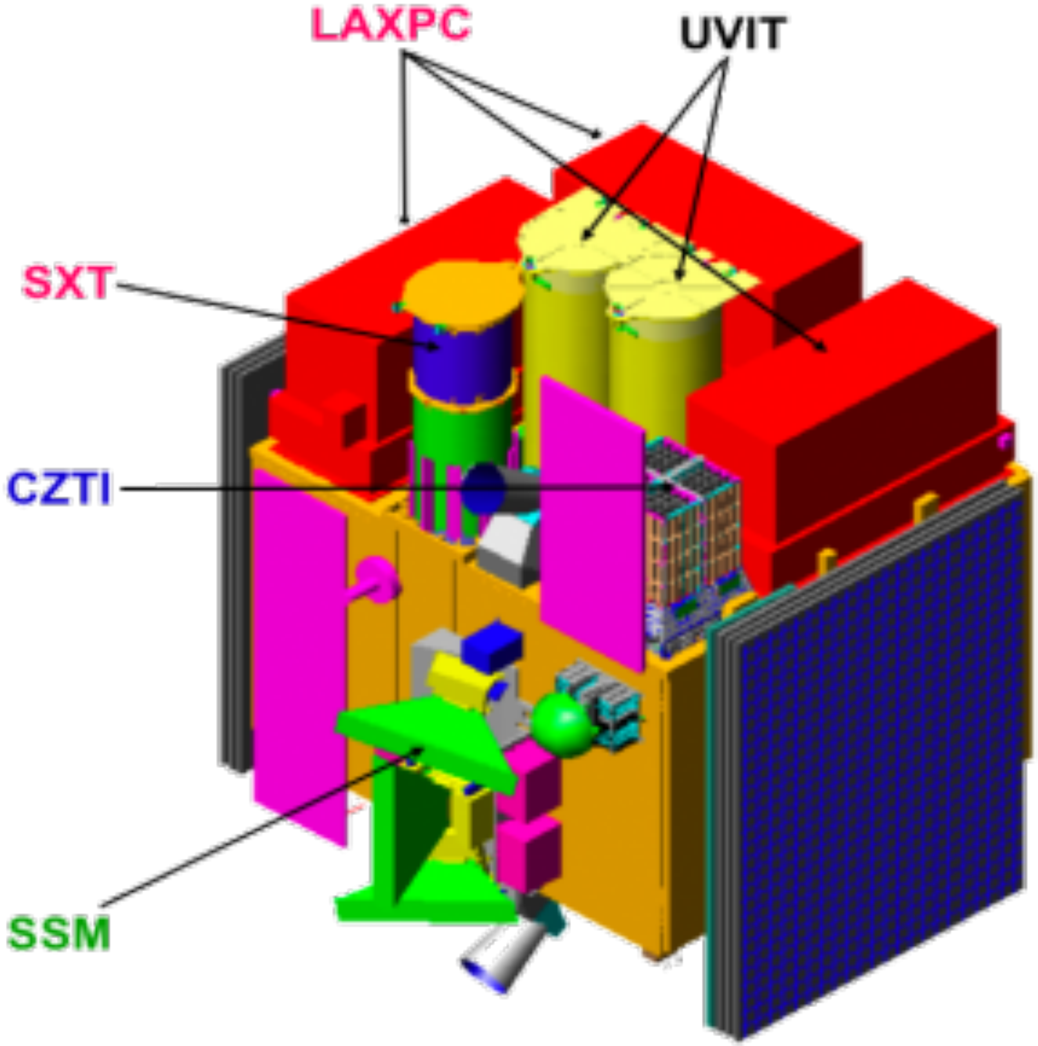
"X-ray Polarisation in Astrophysics – A new window about to open",
28 August 2014, Stockholm, Sweden

Outline

- Astrosat
  - Introduction
  - CZT-Imager
- X-ray Polarimetry with CZTI
  - Proof-of-Concept
  - Geant4 simulations
  - Experimental verification
  - Expected sensitivity
- Summary

Astrosat



India's first dedicated satellite

for Multi-wavelength Astronomy

Collaborative project of

- Many premier Indian research institutes
- + two international parterres

Astrosat

- 650 km, near equatorial orbit
- Launch by Indian PSLV in 2015 (Q2/Q3)
- Observatory class, Proposal driven mission from 2nd year

Main scientific focus

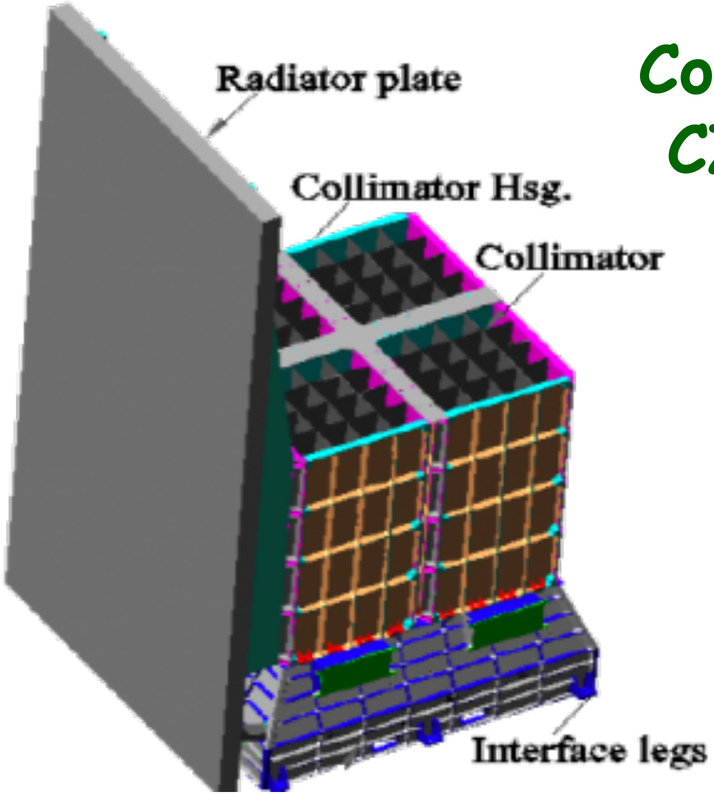
- Simultaneous multi-wavelength monitoring of broad range of cosmic sources.
- Sky surveys in the hard X-ray and UV bands.
- Broadband spectroscopic studies of X-ray binaries, AGN, SNRs, clusters of galaxies and stellar coronae.
- Studies of periodic and non-periodic variability of X-ray sources.
- Monitoring the X-ray sky for new transients.

Astrosat

Five Instruments

- LAXPC: Large Area X-ray Proportional Counters
  - $A_{eff} \approx 6000$ cm^2; FOV =1° X 1°; 3-80 keV; Res: 9% @ 22 keV
- CZTI: Cadmium-Zinc-Telluride Imager with Coded Aperture Mask
  - $A_{eff} \approx$ 500 cm^2; FOV = 6° X 6°;10 – 100 keV; Res: 6% @ 60 keV
- SXT : Soft X-ray Telescope using conical-foil mirrors
  - $A_{eff} \approx 200$ cm^2 ; FOV = 0.5°; (~3' res); 0.3-8 keV; Res: 2% @ 6 keV
- SSM : Scanning Sky Monitor with 3 PSPCs and CAM
  - $A_{eff} \approx 30$ cm^2 (each); 2-20 keV. Res: 20 % @ 6 keV
- UVIT : Ultraviolet Imaging Telescope
  - Two telescopes each with 38 cm aperture; N-UV, F-UV and visible bands.

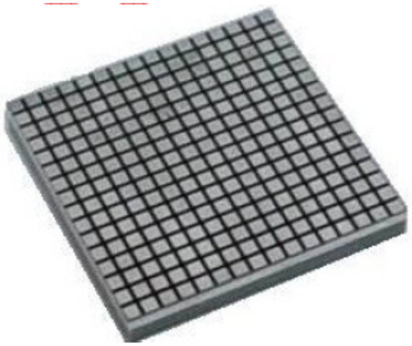
CZT-Imager



Coded Mask imaging with pixilated CZT detectors

- Total area 1024 cm^2
- Total pixels 16384
- Pixel size 2.5 x 2.5 mm^2
- Field of view 6° x 6°
- Angular resolution 8'
- Energy resolution 6 % (@60 keV)
- Sensitivity 3σ detection of 0.5 mCrab source in 10^4 s

Orbotech CZT modules



- 4 x 4 cm^2 (16 x 16 pixel)
- 5 mm thick
- ASIC based readout (2 x 128 ch. ASIC)
- Total 64 modules (16 in 4 quadrants)

X-ray polarimetry with CZTI

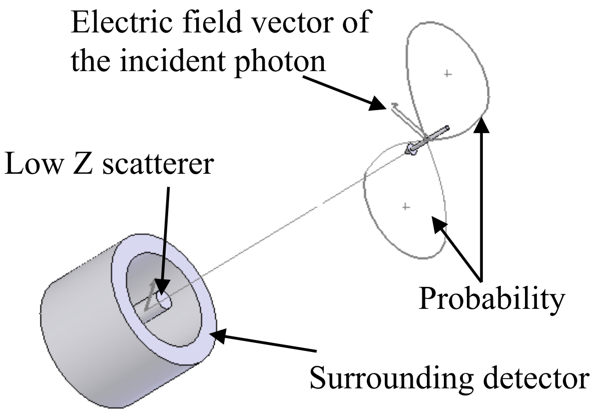
- Pixilated detectors in principle can measure polarization
  - Many attempts to measure polarization from instruments not optimized for polarimetry (RHESSI, Integral-IBIS, Integral -SPI)

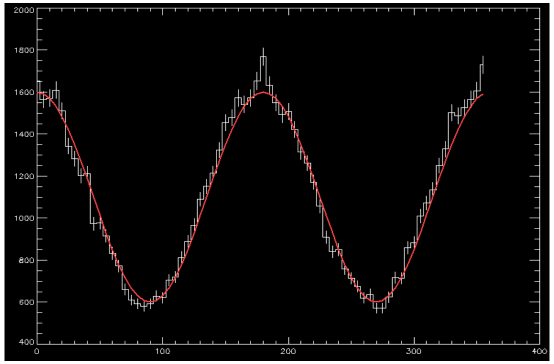
- **Can Astrosat CZTI measure X-ray polarization?**
  - May be above 100 keV (due to scattering probability / threshold)

  (Capability in modules? Preserved in data? Meaningful sensitivity?)

Compton polarimetry

$$d\sigma = \frac{r_e^2}{2}\left(\frac{\nu'}{\nu}\right)^2\left(\frac{\nu}{\nu'}+\frac{\nu'}{\nu}-2\sin^2\theta\cos^2\varphi\right)d\theta d\varphi$$





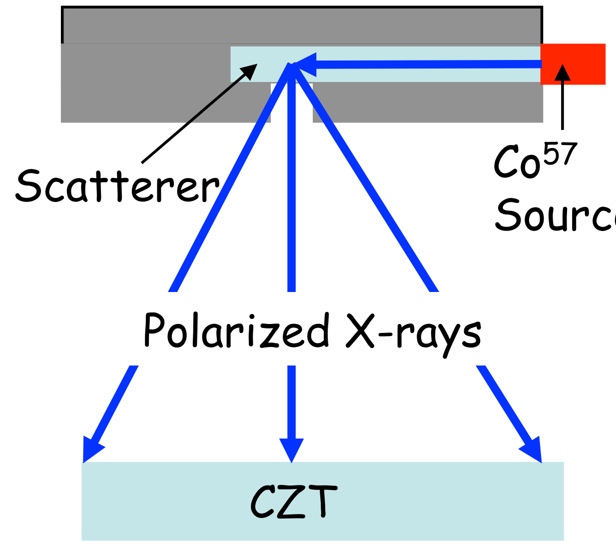
$$\mu = \frac{C_{max} - C_{min}}{C_{max} + C_{min}} \qquad P = \frac{\mu_P}{\mu_{100}}$$

$$MDP = \frac{4.29}{\mu_{100}R_{src}}\sqrt{\frac{(R_{src}+R_{bkg})}{T}}$$

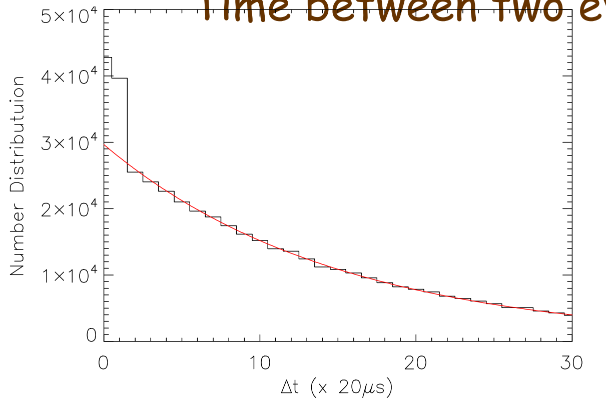
For scattering polarimetry with Pixilated detectors ➔ azimuthal bins are unequal

Proof-of-Concept Experiment

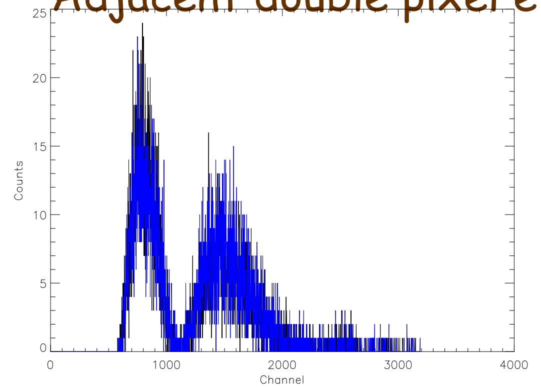
- Verify multi-pixel capability of CZTI modules
- ~70 % Polarized beam produced by 90° Compton scattering of 122 keV X-rays from Co^{57}
- Energy of polarized X-rays ~100 keV
- Time tagging → 20 μs

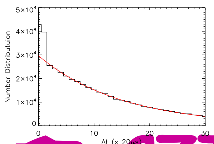


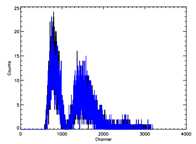
Time between two events



Adjacent double pixel events, E2/E1>2



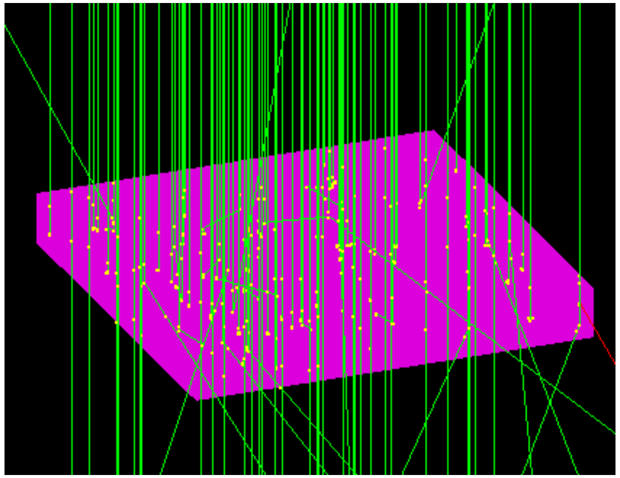


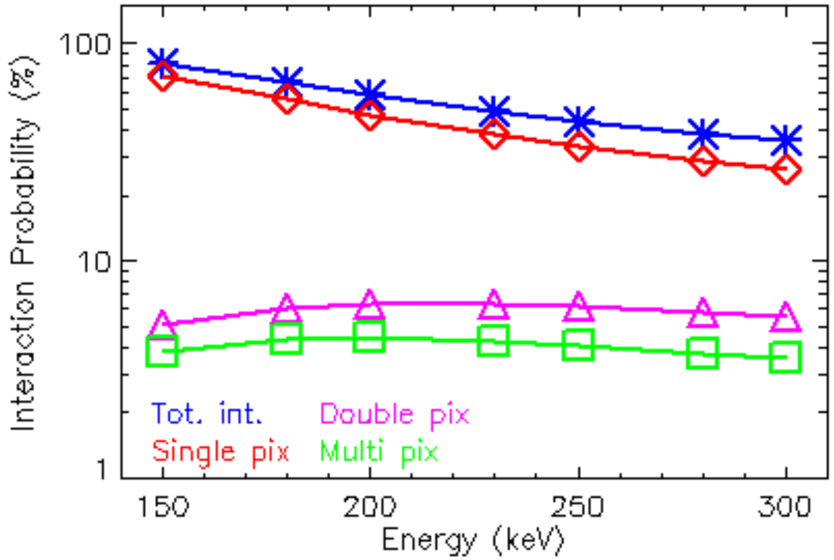


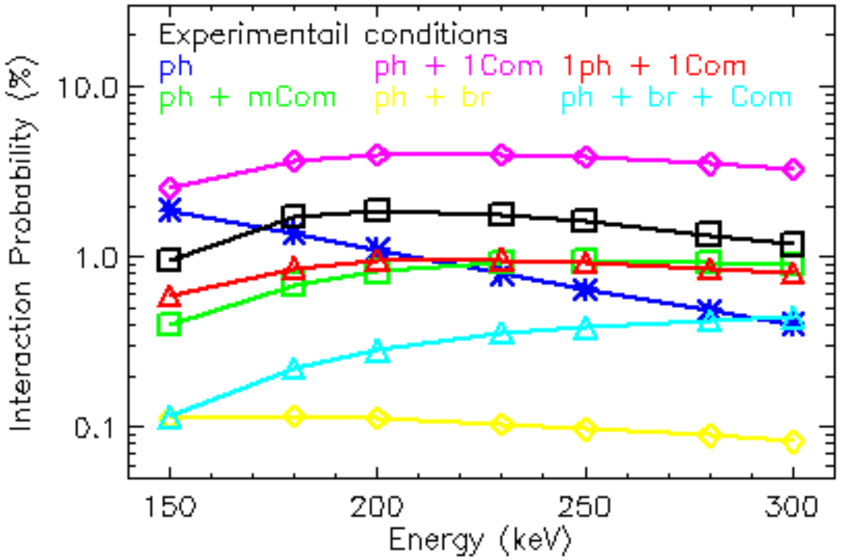
☛ **CZTI Modules can detect simultaneous multi-pixel events**

Geant4 Simulations for CZTI

- Simulate interaction of photons with 40x40x5 mm^3 CZT (Low Energy Electro-magnetic processes)
- Energy range → 100 to 300 keV in 10 steps
- Unpolarized + 100 % polarized beam at 9 angles
- 10 Million photons at each step
- Record absolute positions of the primary interaction and up to 5 secondary interactions
- Pixilate with 2.5 mm pixel
- Investigate number of pixels as well as number / type of interactions

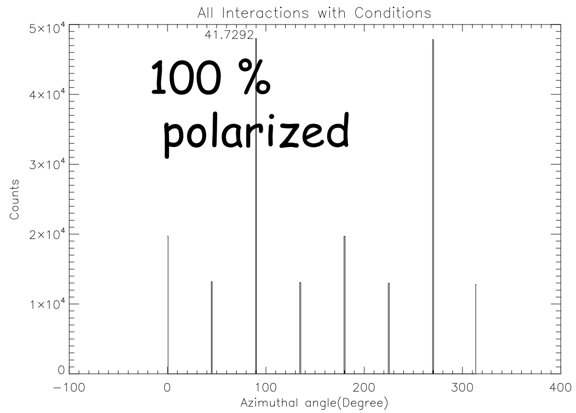


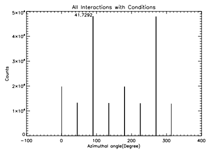


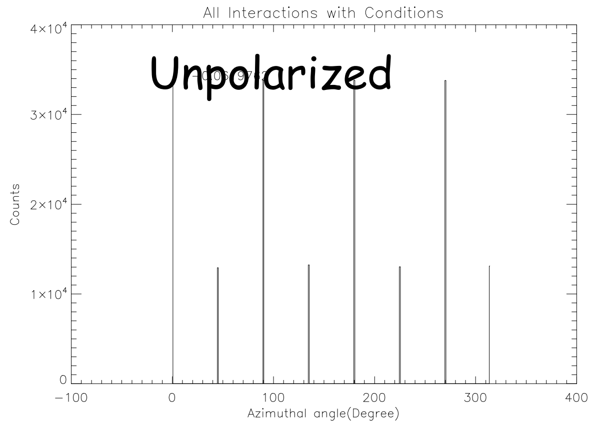


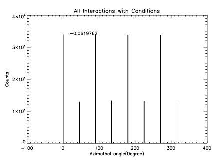
Modulation Curve

Generate 8 bin azimuthal histogram with low energy pixel as scattering pixel





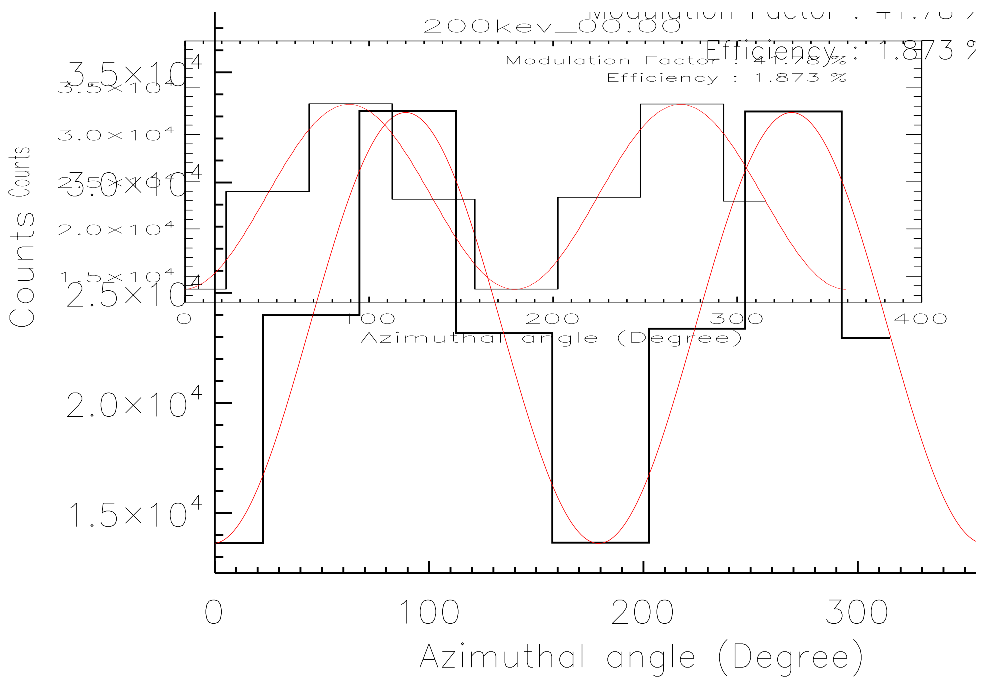




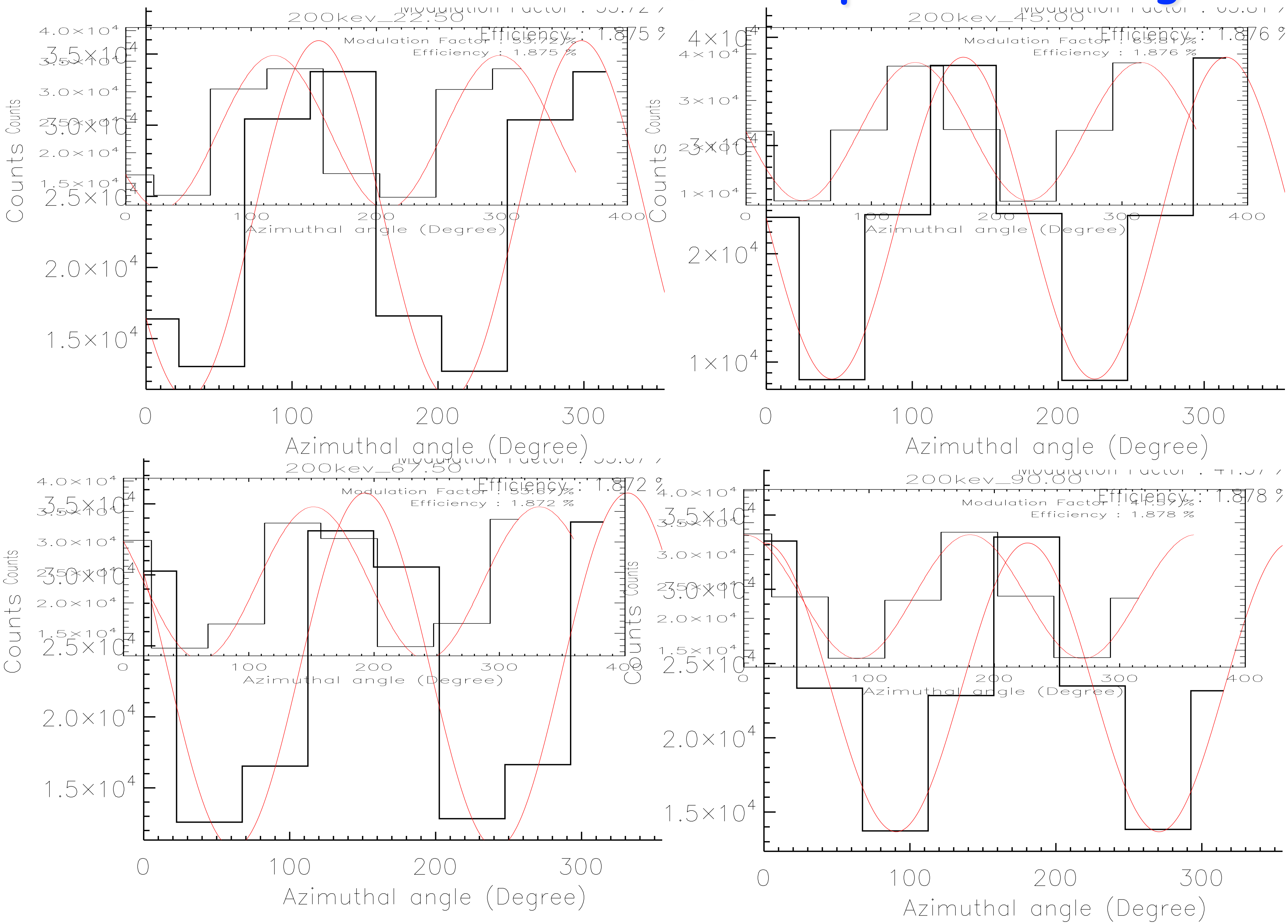
- Modulation curve has only 8 bins, which have non uniform angular coverage
- Can be normalized with modulation curve for unpolarized beam

$$N_{i,nor} = \frac{\overline{M}_{unpol}}{M_{i,unpol}} N_{i,obs}$$

(Lei et al., 1997)



Azimuthal Modulation at different polarization angles

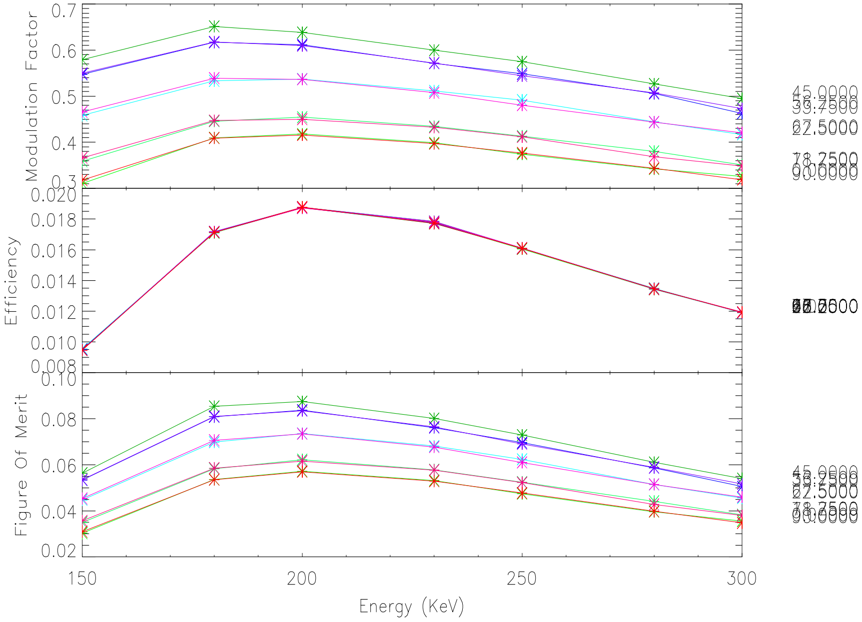


Azimuthal Modulation at different polarization angles

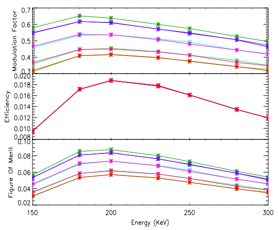
- Modulation factor is now dependent on the polarization angle

  ➔ Figure of Merit → $FoM = \mu_{100} \cdot \sqrt{\varepsilon}$

  is function of both energy and polarization angle

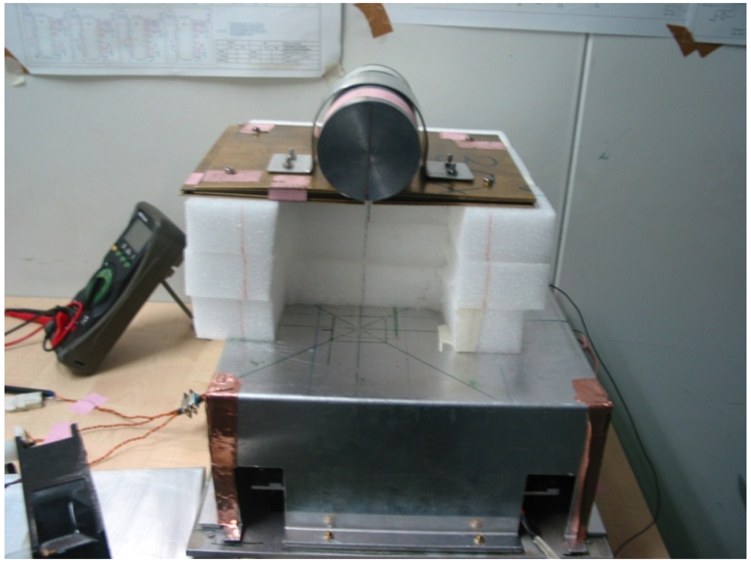


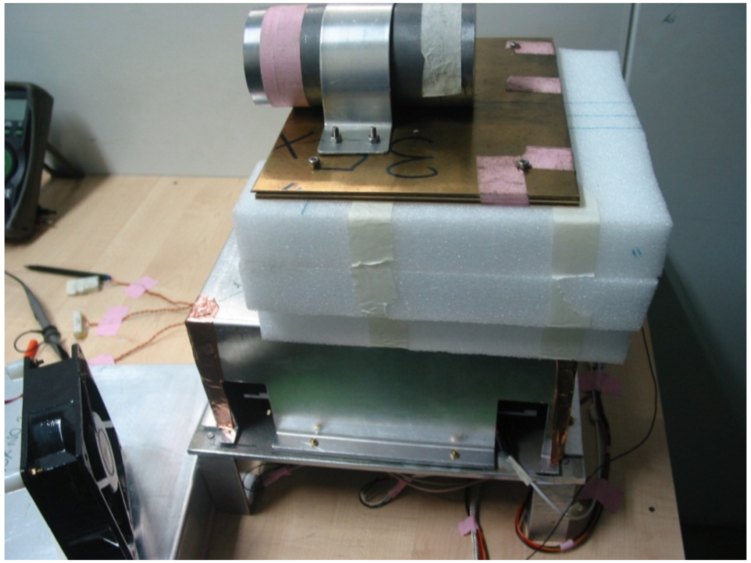
Pol.Angle	Average MF (%)
0	36.83
11.25	40.52
22.50	48.46
33.75	55.19
45.00	58.05
56.25	55.33
67.50	48.47
78.75	40.34
90.00	36.82



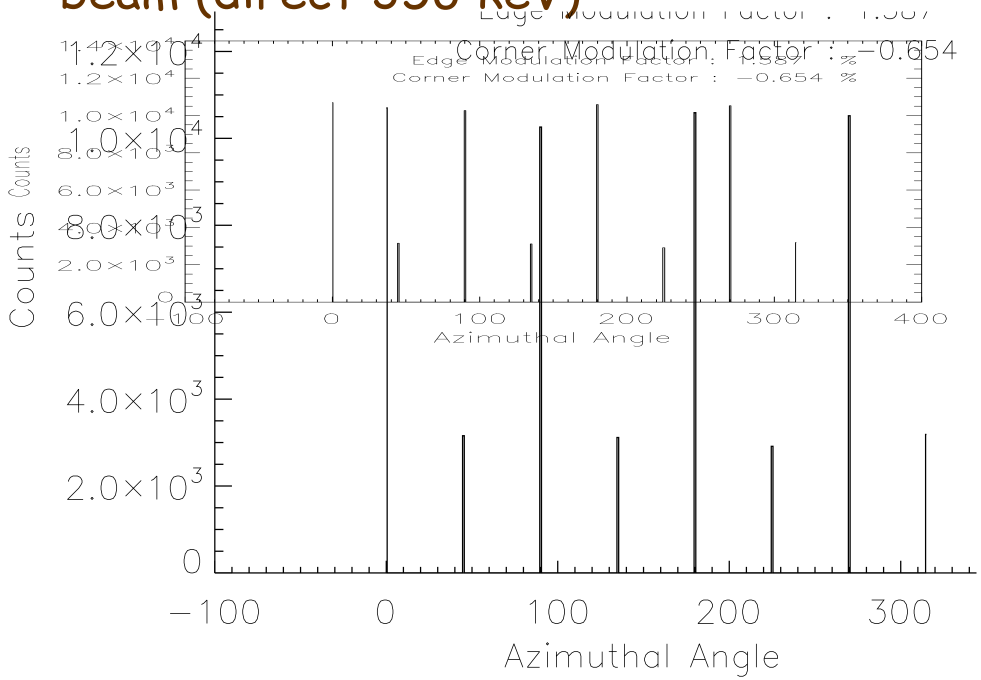
- Significant modulation → Polarization measurement possible
- Angle dependent modulation → opportunity of cross verification

Experimental Verification



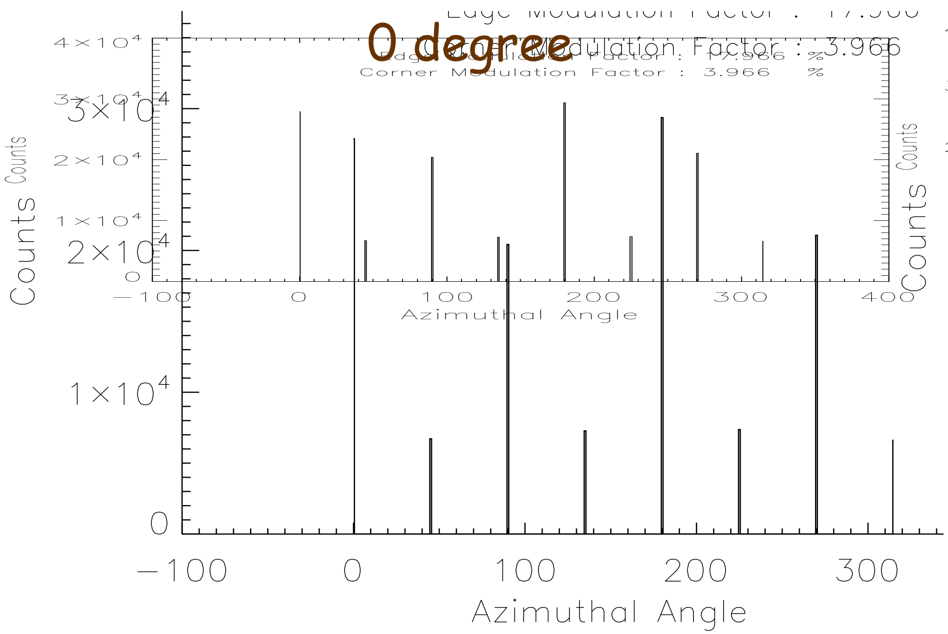


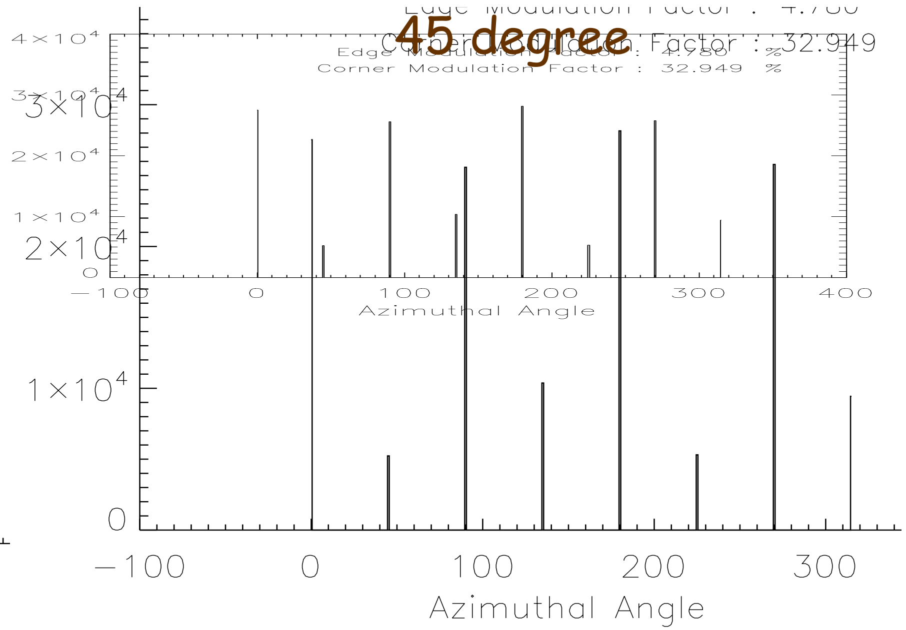
- Detection of polarized X-rays with CZT-I Flight electronics
- Polarized X-rays by Compton scattering of 356 keV from ^{133}Ba in 70 – 107 deg.
  - Incident energy: ~190 – 240 keV
  - ~70% polarized beam
- Measurements at four different incident angles 0°, 45°, 90° and 135° + unpolarized beam (direct 356 keV)

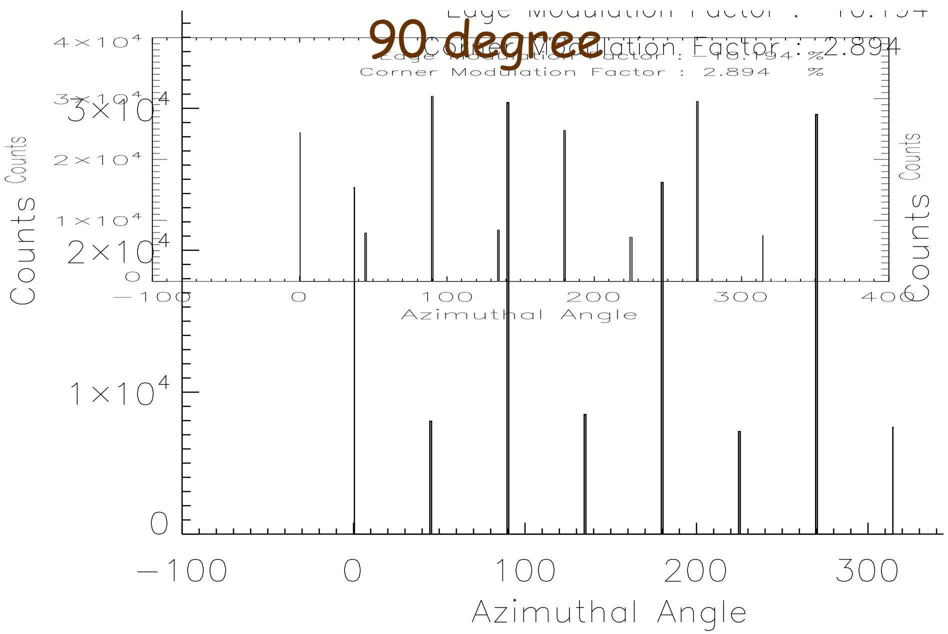


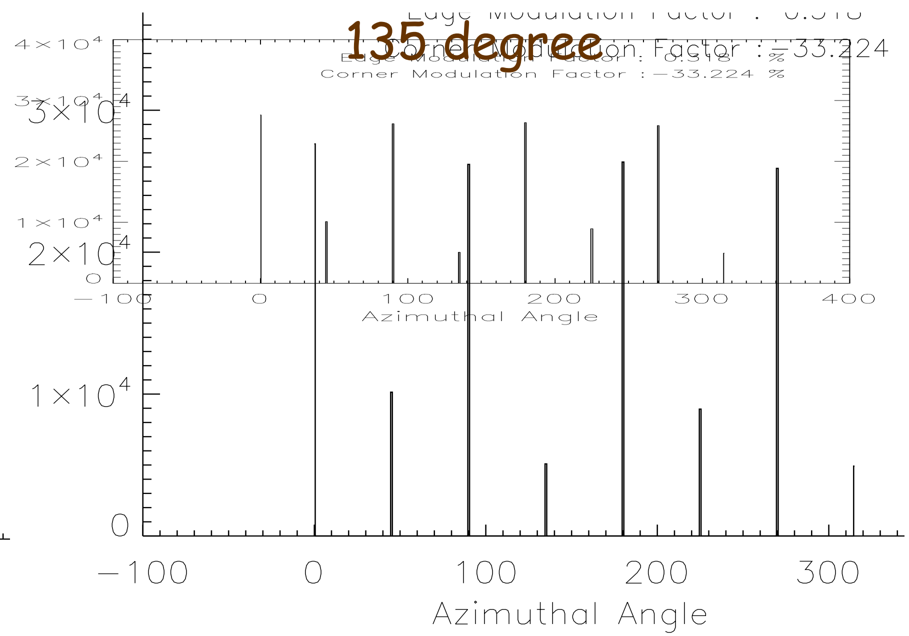
Modulation curve for unpolarized beam

Observed Modulation for Polarized Beam



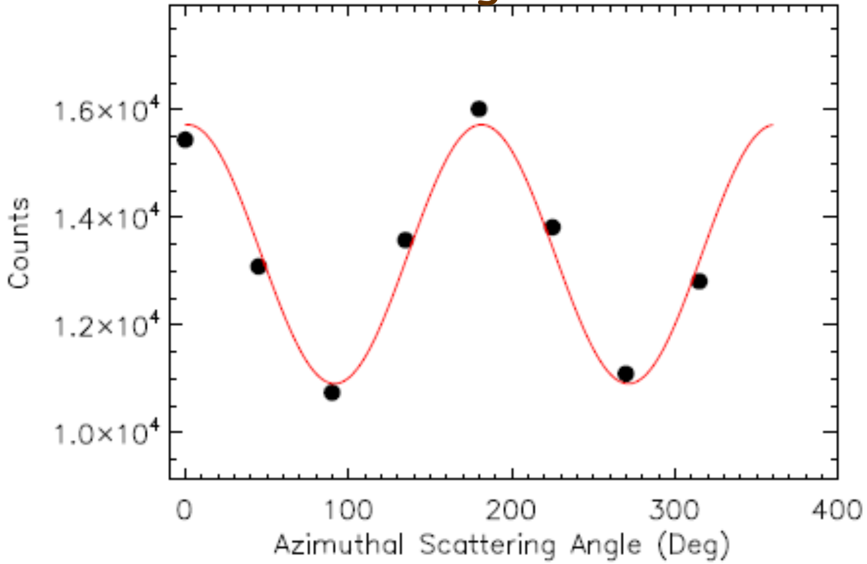




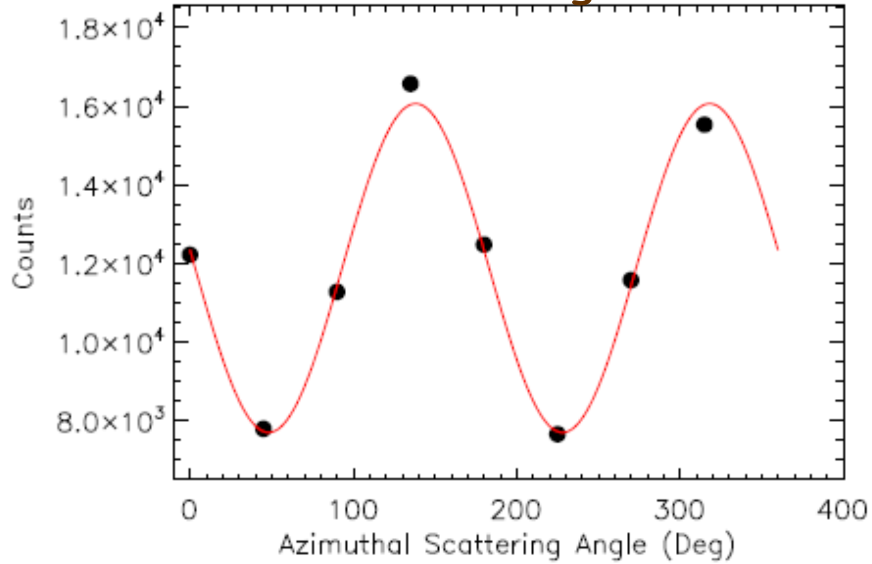


Normalized Modulation Pattern

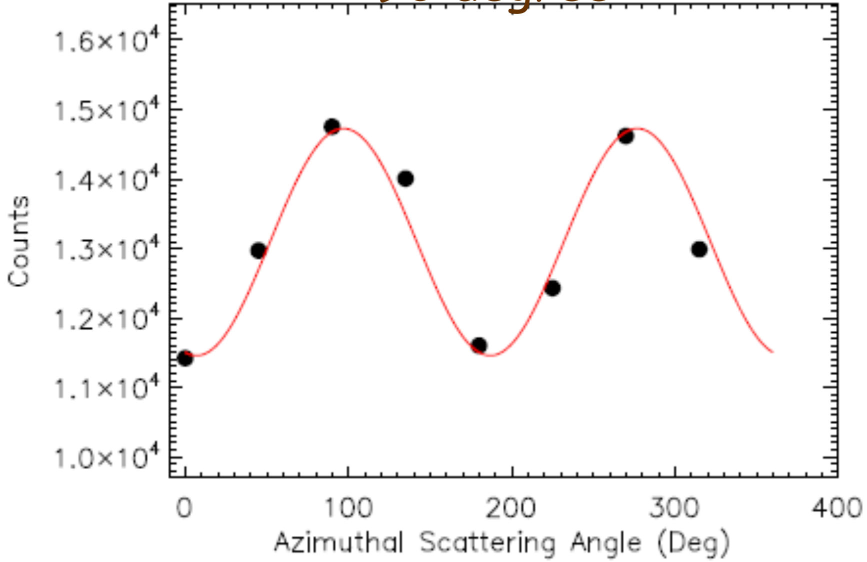
0 degree



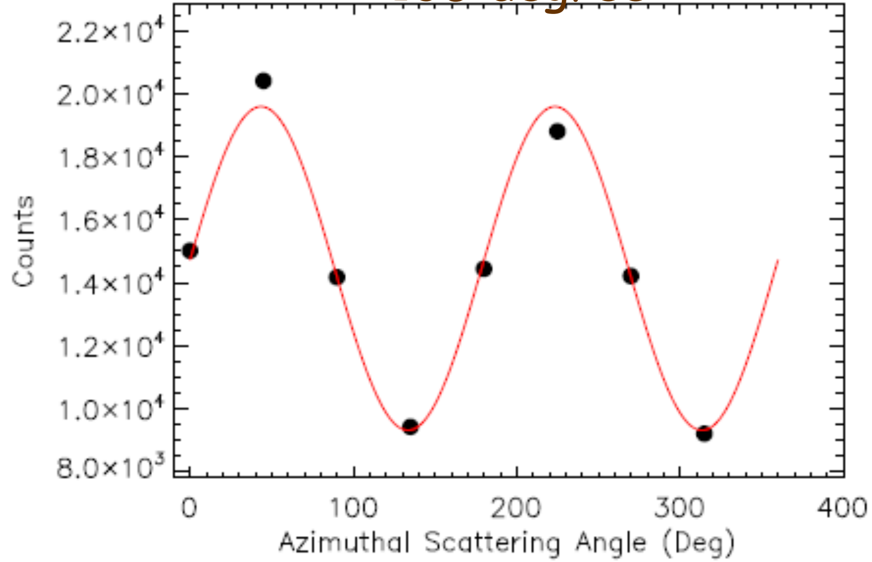
45 degree



90 degree

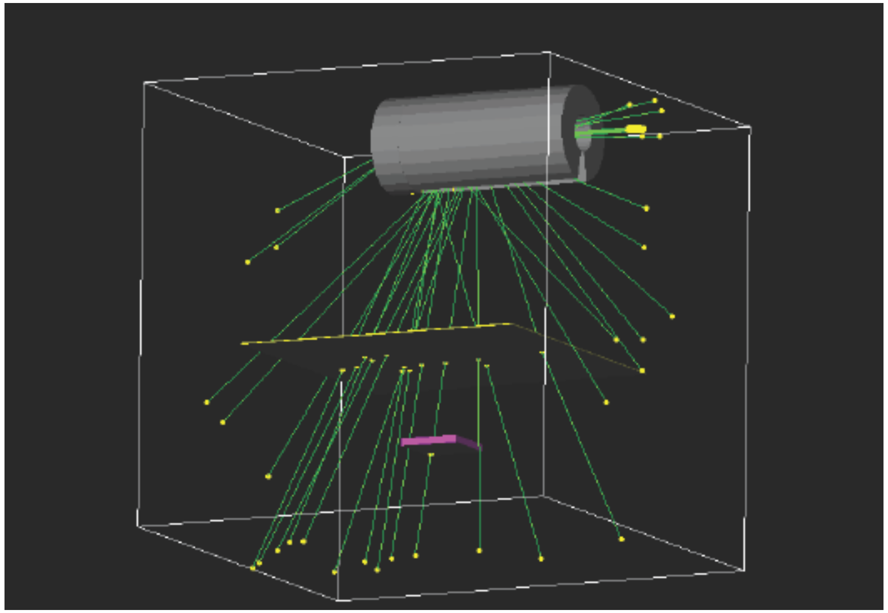


135 degree



Validation of the Simulations

- Observed modulation factor is less then simulated one for 100% polarized X-rays
  - As expected because of partially polarized beam
- Verify with Geant4 simulation of the experimental setup



Modulation factors (%)

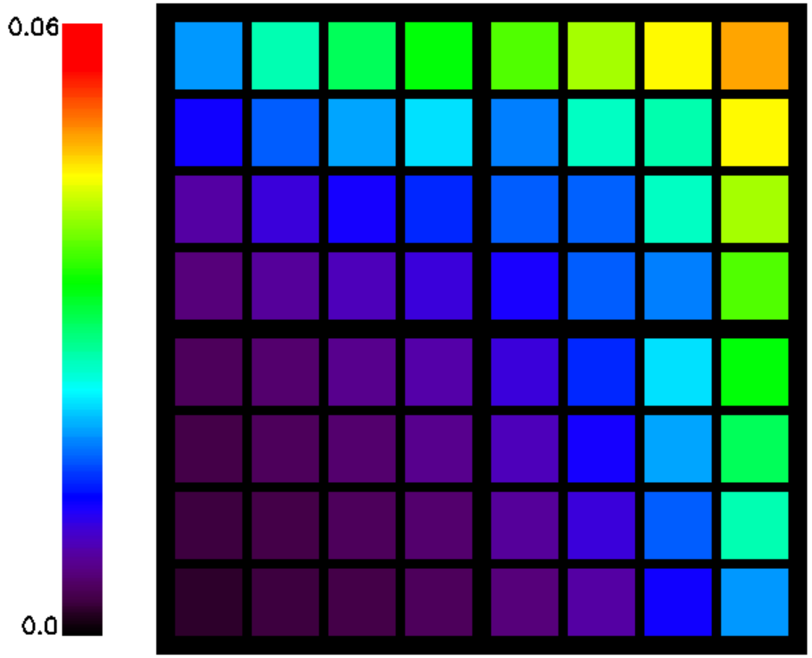
Angle	Obs.	Sim.
0°	19.68	20.74
45°	36.99	37.43
90°	11.96	22.06
135°	36.83	38.40

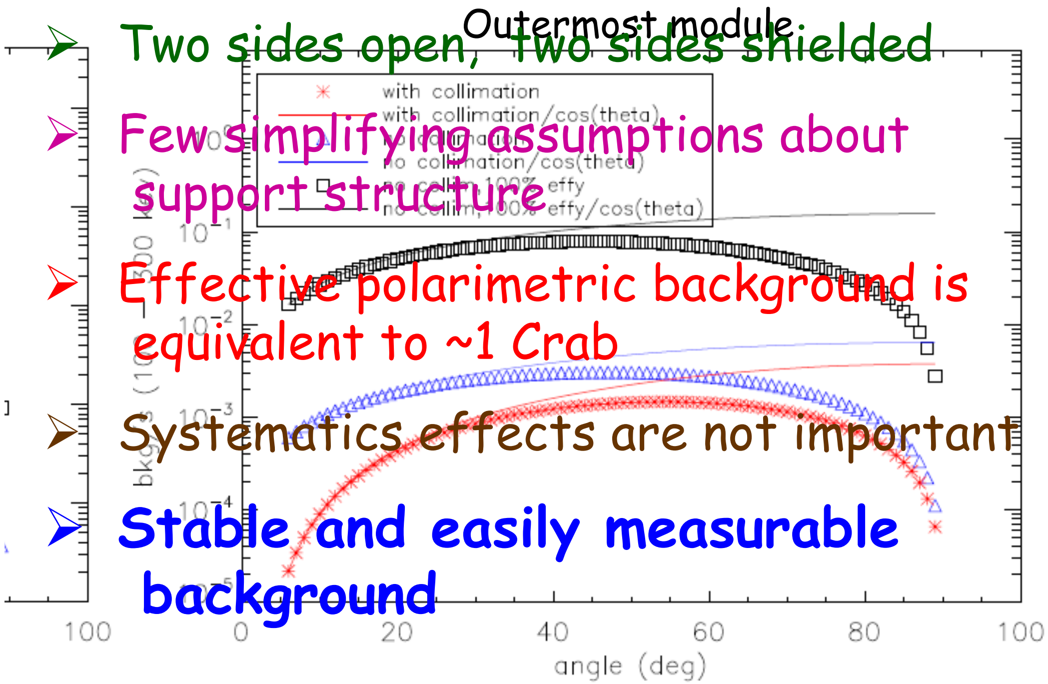
- Observed and simulated modulation factors match within 1%
  → after addition of the instrumental background

⇨ **Simulations with 100 % polarized beam do indicate realistic modulation factors**

Polarimetric Background

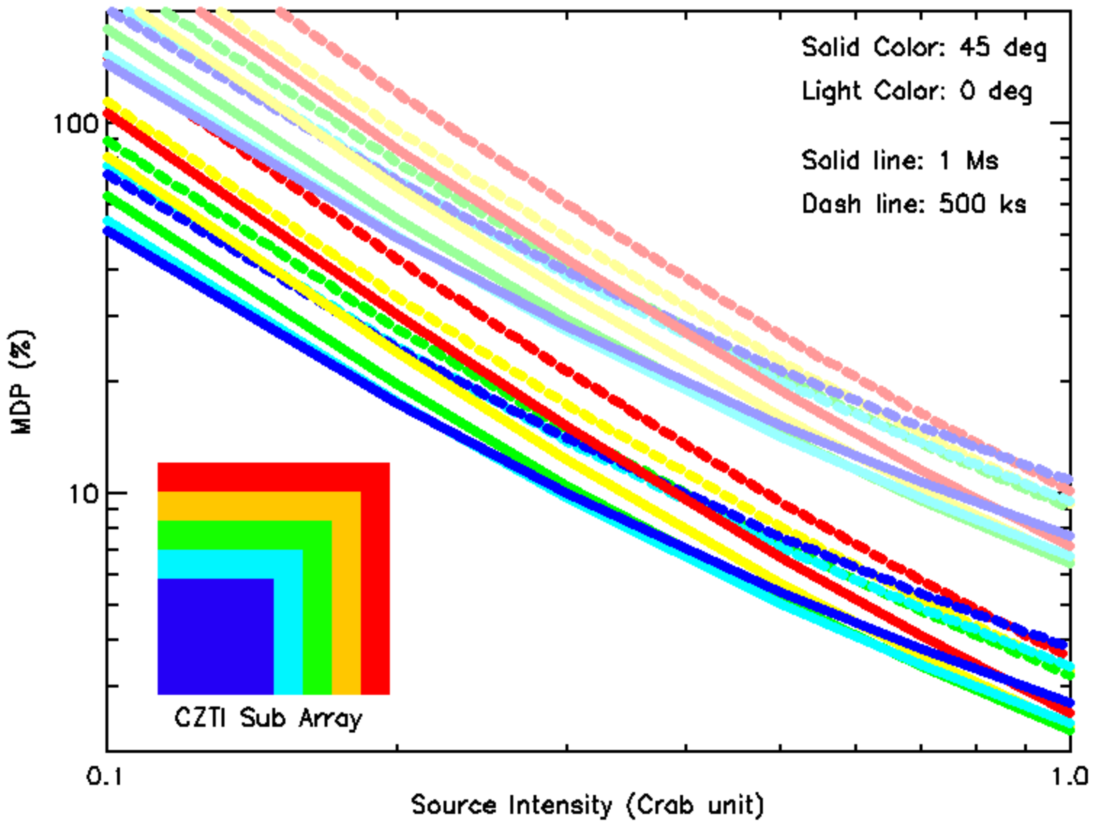
- All double pixel events satisfying filtering criteria
  - ➔ Inst + Inst, Src + Src, Bkg + Bkg and their combinations
  - ➔ Compton scattering of cosmic X-ray background photons
- CZTI mask and shielding designed up to 150 keV
- Most important component (99.99 %) is Compton scattering of cosmic diffuse X-ray background
  - Different for different module due to varying shielding
  - Estimated for each module separately





- Two sides open, Two sides shielded
- Few simplifying assumptions about support structure
- Effective polarimetric background is equivalent to ~1 Crab
- Systematics effects are not important
- **Stable and easily measurable background**

Polarimetric Sensitivity of CZTI



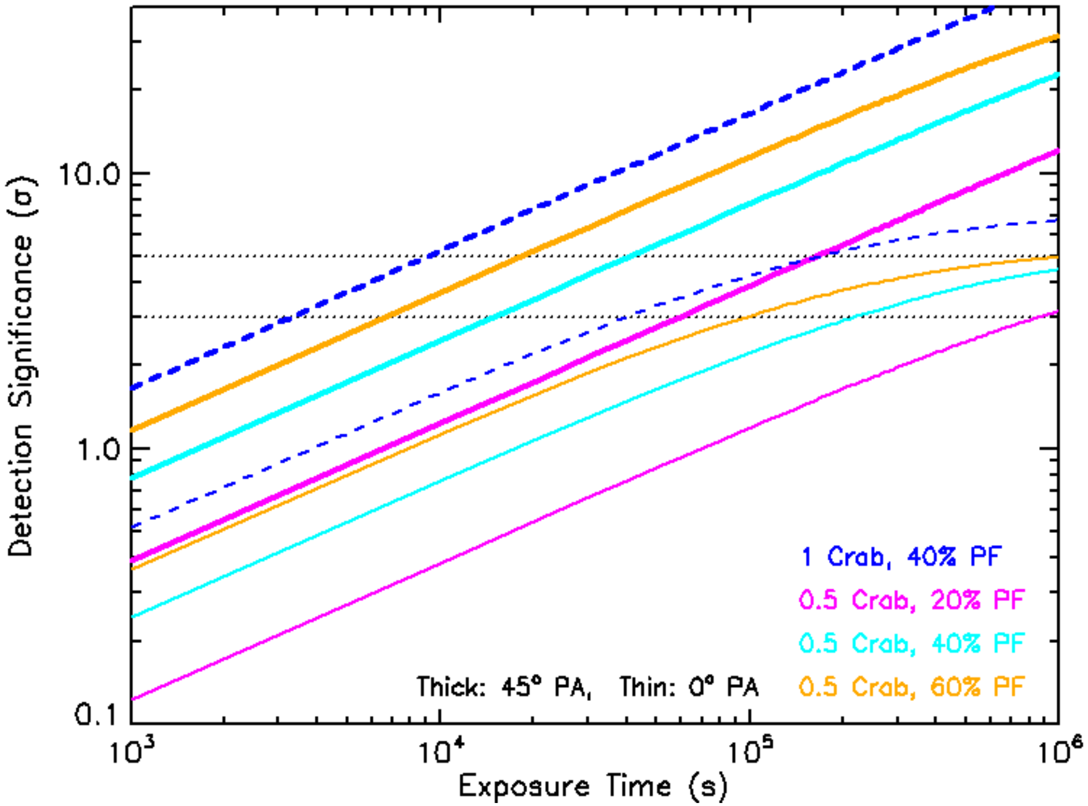
Expected MDP		
1 Crab, 1 MS	Known PA	~2%
	Unknown PA	~8%
0.5 Crab, 500 ks	Known PA	~7%
	Unknown PA	~20%

- Different sensitivity at different polarization angle
  - ➔ Any measurement can be verified at different S/C role angle
- Slightly different sensitivity for sub-arrays
  - Sub-array selection can be optimized at analysis stage

Too demanding on source intensity and exposure time?

Polarization detection time scale

(not so bad for highly polarized sources)



Uncertainty in Pol. Deg.

$$\frac{\sigma_P}{P} = \sqrt{\frac{\sigma_\mu^2}{\mu^2} + \frac{\sigma_{\mu_{100}}^2}{\mu_{100}^2}}$$

- $\mu_{100}, \sigma_{\mu_{100}}$ depend on PA
- determined by fitting to simulated library
- For bright and highly polarized sources
  polarization can be detected 50 – 100 ks

Scientifically meaningful?

- Pulse phase resolved polarimetry → Crab
- Jet contribution to X-rays in BHB → Cyg X-1, GRS1915+105, Transients
- GRB polarimetry → after studying the off-axis response (under progress)

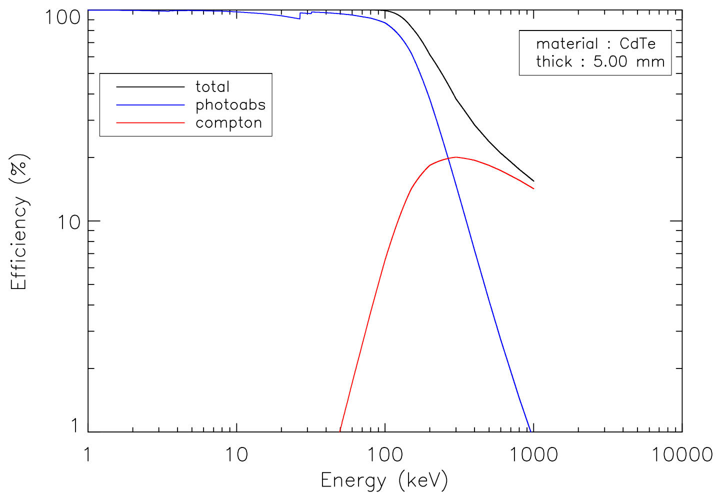
Summary

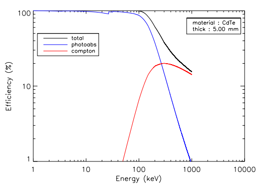
- 100 – 250 keV polarimetry with Astrosat-CZTI is possible for bright sources
  - MDP of ~8 % for a Crab like source in 1 Ms
  - For highly polarized source, polarization signature can be detected 50 – 100 ks
- No additional requirement, only from available raw CZTI data in the standard mode
- Polarimetric energy range (100 – 250 keV) is not the primary spectroscopic energy range
  - Mask and other structural elements are transparent
- Polarimetry is also possible for off-axis sources!!
  - Good opportunity for GRB polarimetry

Real test → Actual background level, No polarization

Thanks...

X-ray polarimetry with CZT-Imager





Significant Compton scattering probability ~ 10 – 20 % in 100 – 300 keV

Compton polarimetry can be applicable for CZTI at energies (> 100 keV) beyond its primary spectroscopic energy range

- **Can Astrosat CZTI measure X-ray polarization?**
  - Multi-pixel capability in the Orbotech CZT modules?
  - If yes, whether CZTI will have meaningful sensitivity?
  - Polarimetric information preserved by data processing?

Brightest sources from BAT 70m catalog

fv: Binary Table of BAT_70m_catalog_20nov2012.fits[1] in C:/Documents and Settings/Santosh/My Documents/Dropbox/Temp…

File Edit Tools Help

Select	BAT_NAME	RA	DEC	COUNTERPART_NAME	FLUX	TYPE
All	19A	E	E	30A	E	21A
Invert	Modify	deg Modify	deg Modify	Modify	10^-12ergs/sec/cm^2 Modify	Modify
1	SWIFT J0534.6+2204	83.626	22.025	Crab	23861.50	PSR/PWN
2	SWIFT J1958.4+3510	299.563	35.202	Cyg X-1	21861.30	HMXB/BH
3	SWIFT J1620.1-1539	244.985	-15.636	Sco X-1	19348.50	LMXB/NS
4	SWIFT J1915.3+1057	288.806	10.967	GRS 1915+105	4325.27	LMXB/BH
5	SWIFT J0902.1-4034	135.529	-40.579	Vela X-1	3931.86	HMXB/NS
6	SWIFT J1703.9-3753	255.970	-37.848	4U 1700-377	3425.23	HMXB/NS
7	SWIFT J1226.6-6244	186.700	-62.782	GX 301-2	2829.08	LMXB/NS
8	SWIFT J2032.5+4055	308.121	40.967	Cyg X-3	2340.28	HMXB/NS
9	SWIFT J1753.5-0130	268.357	-1.456	SWIFT J1753.5-0127	1802.06	LMXB/ BHC
10	SWIFT J1829.4-2346	277.384	-23.785	Ginga 1826-24	1691.54	LMXB/NS
11	SWIFT J1815.8-1403	273.995	-14.022	GX 17+2	1517.32	LMXB/NS
12	SWIFT J1801.1-2504	270.298	-25.072	GX 5-1	1412.12	LMXB/NS
13	SWIFT J1325.4-4301	201.381	-43.026	Cen A	1388.99	Sy2
14	SWIFT J1801.1-2544	270.305	-25.721	GRS 1758-258	1362.69	LMXB/BH
15	SWIFT J1731.9-2444	262.986	-24.754	GX 1+4	1291.36	HMXB/NS
16	SWIFT J1705.9-3624	256.440	-36.430	GX 349+2	1277.29	LMXB/NS
17	SWIFT J1700.8-4139	255.195	-41.657	2MASS J17004888-4139214	1110.15	HMXB/NS
18	SWIFT J0538.8+2620	84.713	26.305	1A 0535+262	1056.49	HMXB/NS
19	SWIFT J1743.7-2946	265.965	-29.741	1E 1740.7-2942	1018.68	LMXB/BH
20	SWIFT J1657.7+3518	254.484	35.332	Her X-1	992.08	LMXB/NS

Go to: Edit cell:

BAT 70m catalog, source > 100 mCrab