X-Ray Polarimetry with *X-Calibur*

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COST Polarisation Workshop, Stockholm, Sweden

26th August, 2014

Outline

The X-Calibur Polarimeter and the InFOCuS Telescope

Calibration and Performance

Current Status

2014 Ft. Sumner Campaign

Space-Borne X-Calibur

Summary

The *X-Calibur*/InFOCuS Team

Washington University

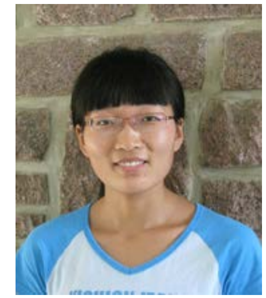
Henric Krawczynski

Matthias Beilicke

Fabian Kislat

Anna Zajczyk

Quingzhen Guo



PI

Research Professor

Post-Docs

Grad Student

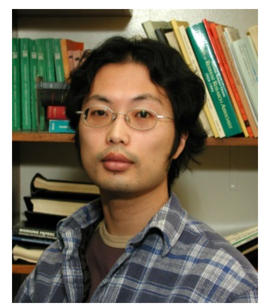
NASA Goddard Space Flight Center

Scott Barthelmy

Takashi Okajima

Thomas Hams

Makoto Sasaki



InFOCuS PI

Research Scientists

Related Recent Papers:

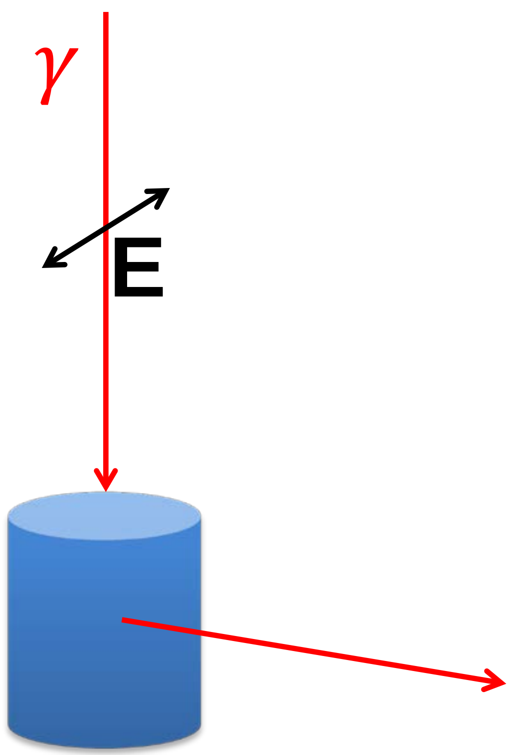
- M. Beilicke et al. 2014, “Design and Performance of the X-ray Polarimeter X-Calibur”, submitted.
- F. Kislat et al. 2014, “An Unfolding Method for X-ray Spectro-Polarimetry”, submitted.
- F. Kislat et al. 2014, “Analyzing the Data from X-ray Polarimeters with Stokes Parameters”, submitted.
- Q. Guo et al. 2013, “Optimization of the Design of the Hard X-ray Polarimeter X-Calibur”, APh, **41**, 63.
- H. Krawczynski et al. 2011, “Prospects of Hard X-ray Polarimetry”, APh, **34**, 550.

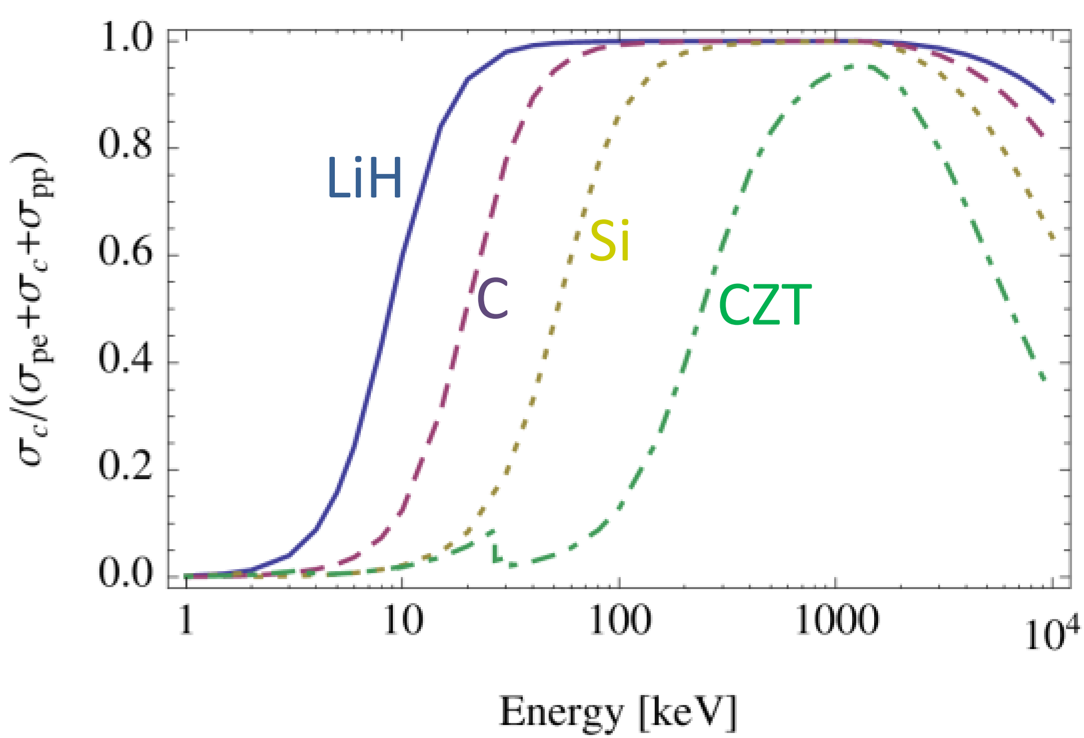
Scattering Polarimeter

- Free-Free Scattering (Raleigh, Thompson, Compton);
- Klein-Nishina Cross Section:

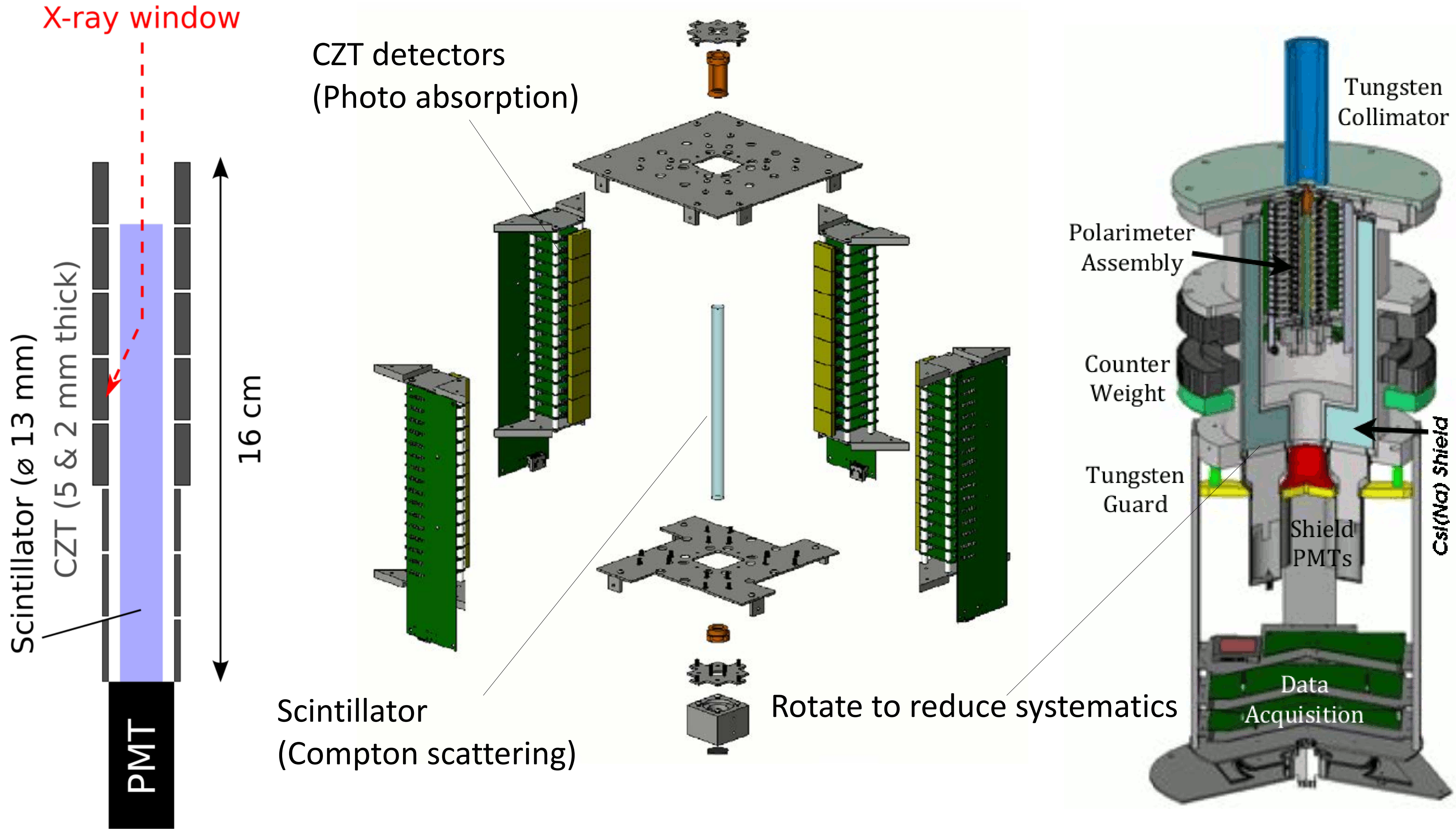
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{r_0^2}{2}\frac{k_1^2}{k_0^2}\left[\frac{k_0}{k_1} + \frac{k_1}{k_0} - 2\sin^2\theta\cos^2\eta\right]$$

- Photons scatter most likely perpendicular to **E**;





The *X-Calibur* Polarimeter



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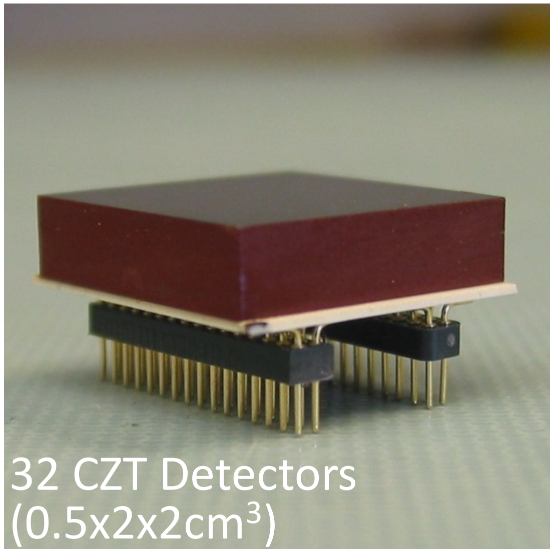
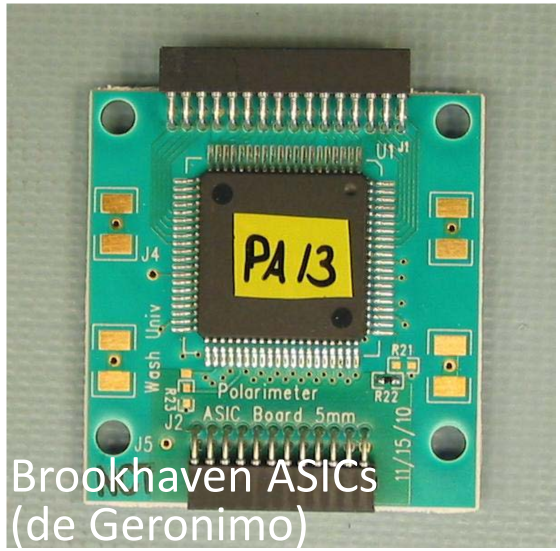
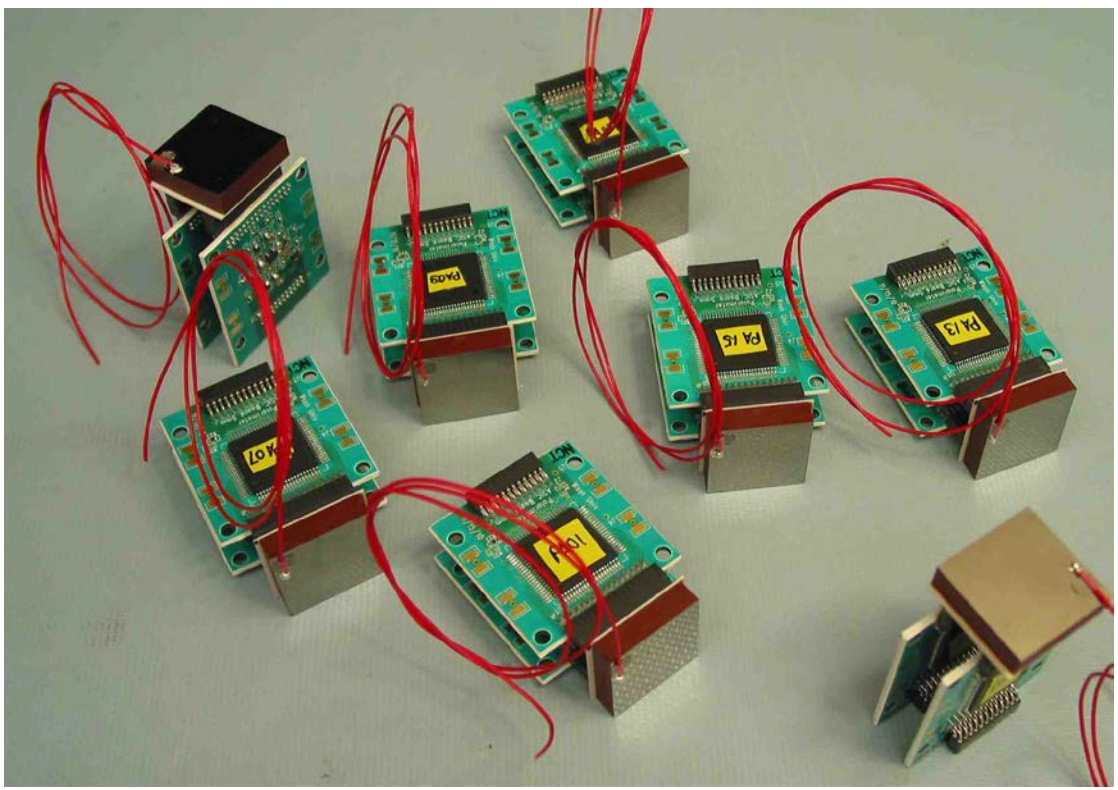
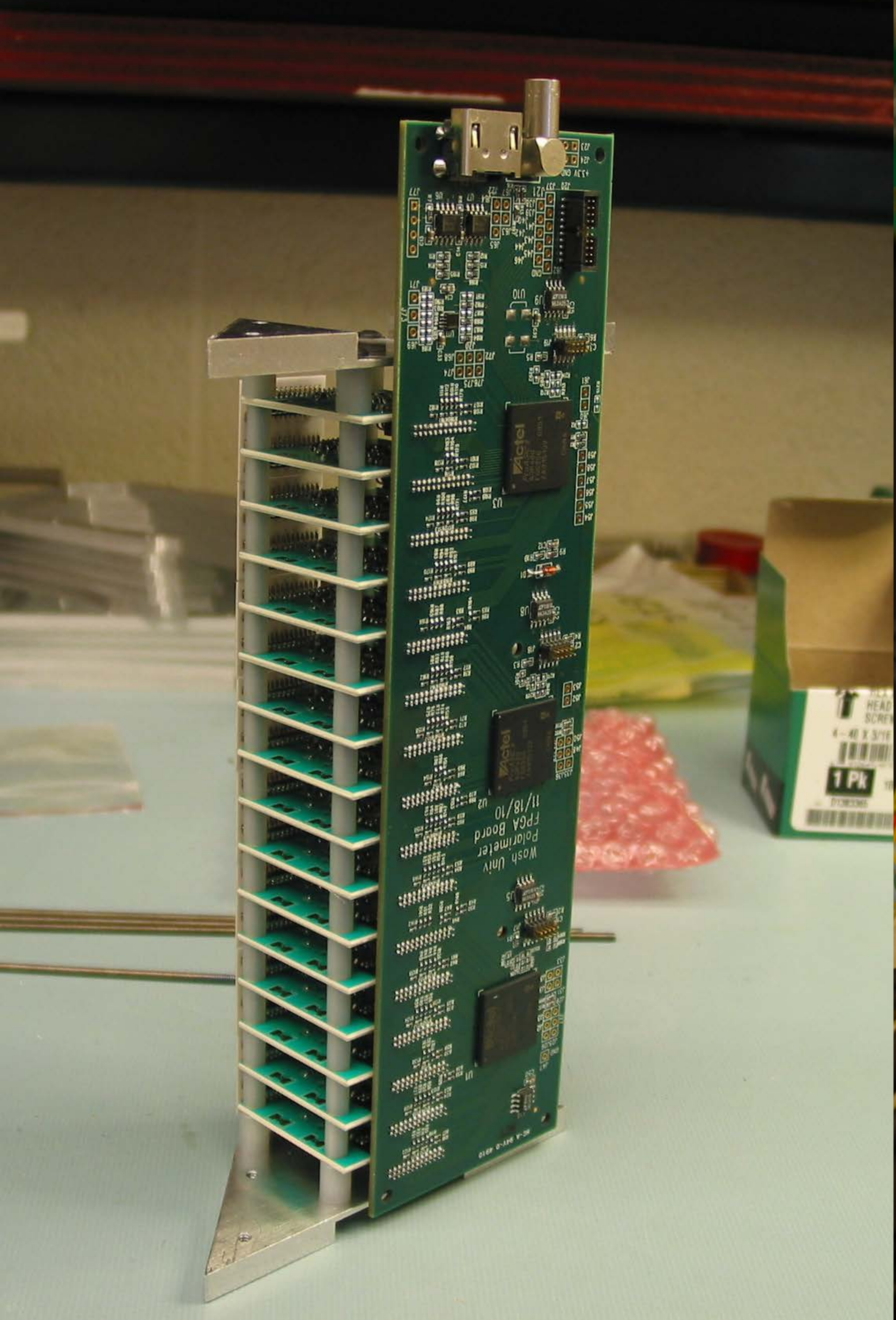






- 32 CZT Detectors
  - 2mm and 5mm thick;
  - 2x2 cm^2 footprint;
  - 64 pixels each.
- Brookhaven ASIC (de Geronimo)
  - 32 channels;
  - 2 ASICs per CZT;
  - Readout noise 2keV FWHM.


Wash Univ
Polarimeter
FPGA Board
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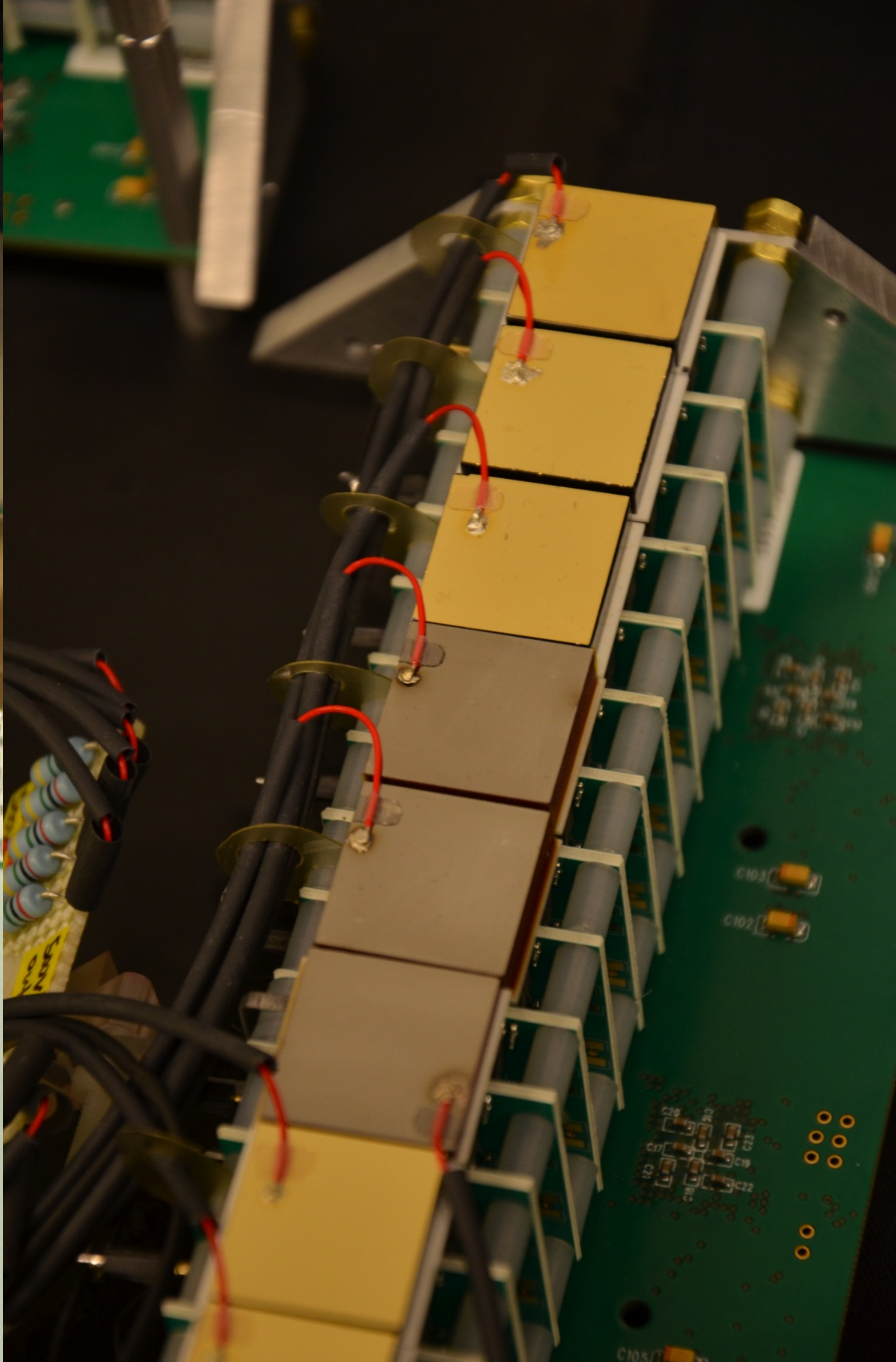
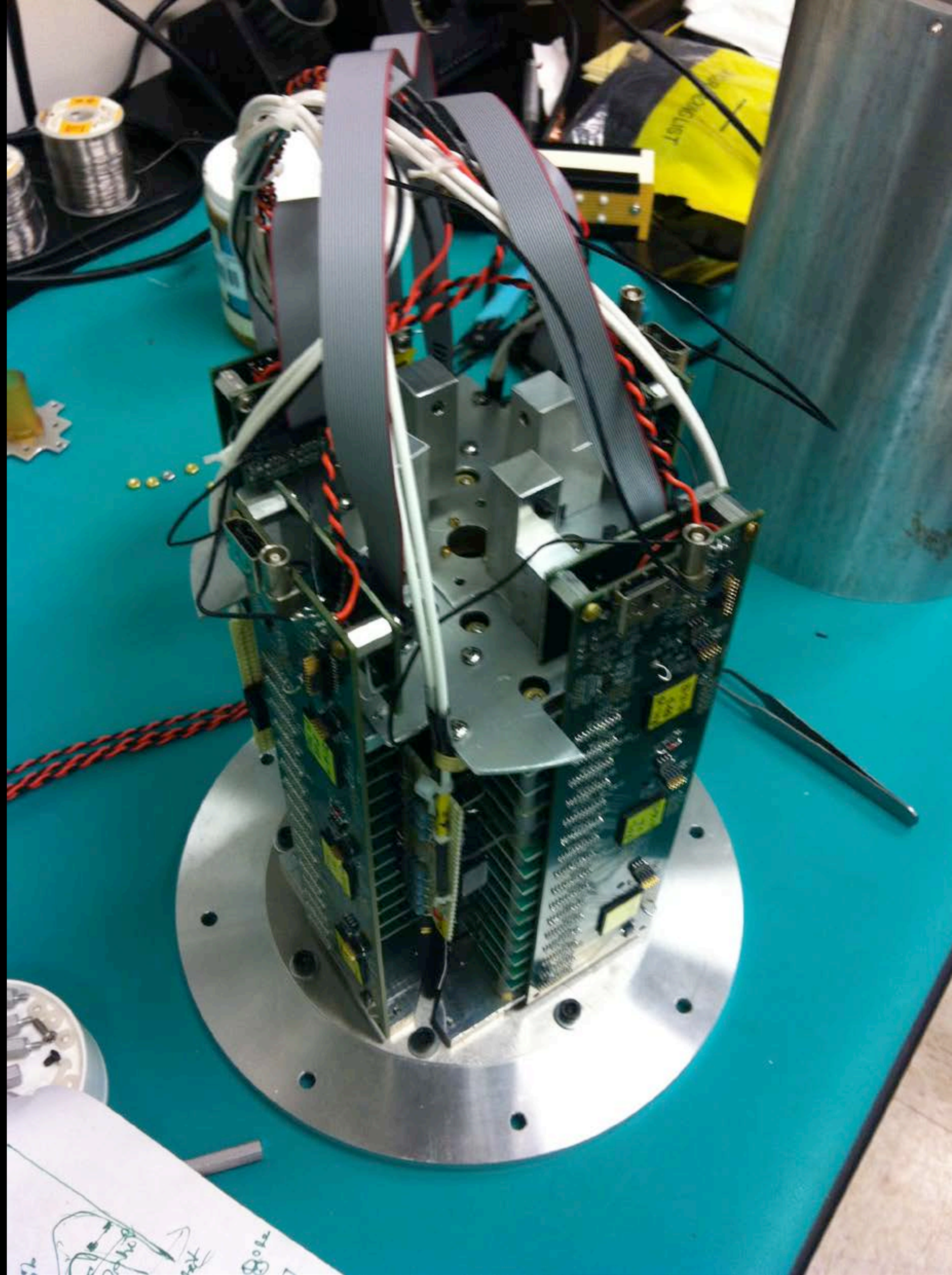
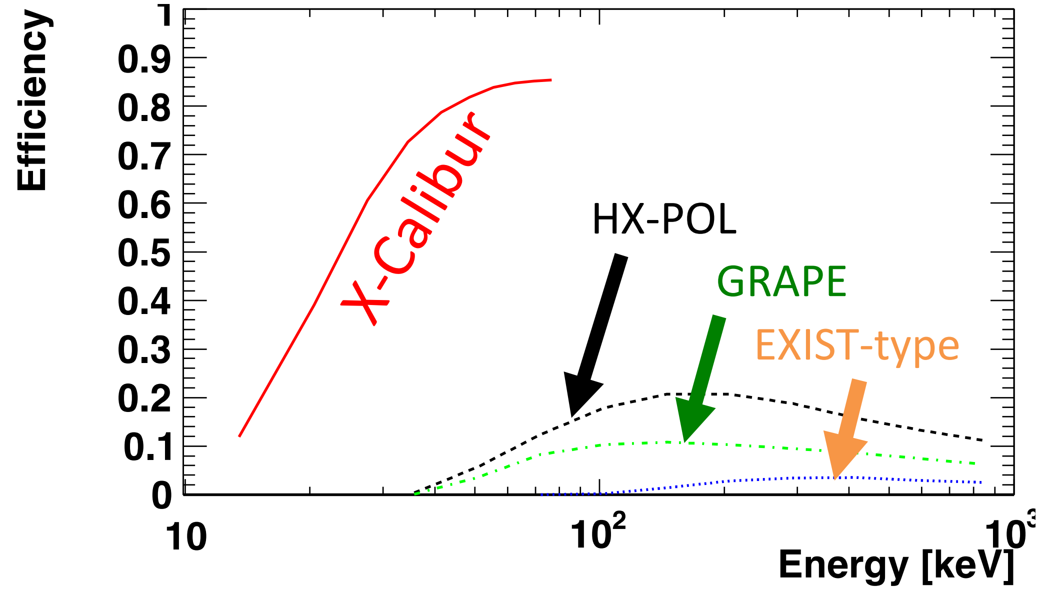
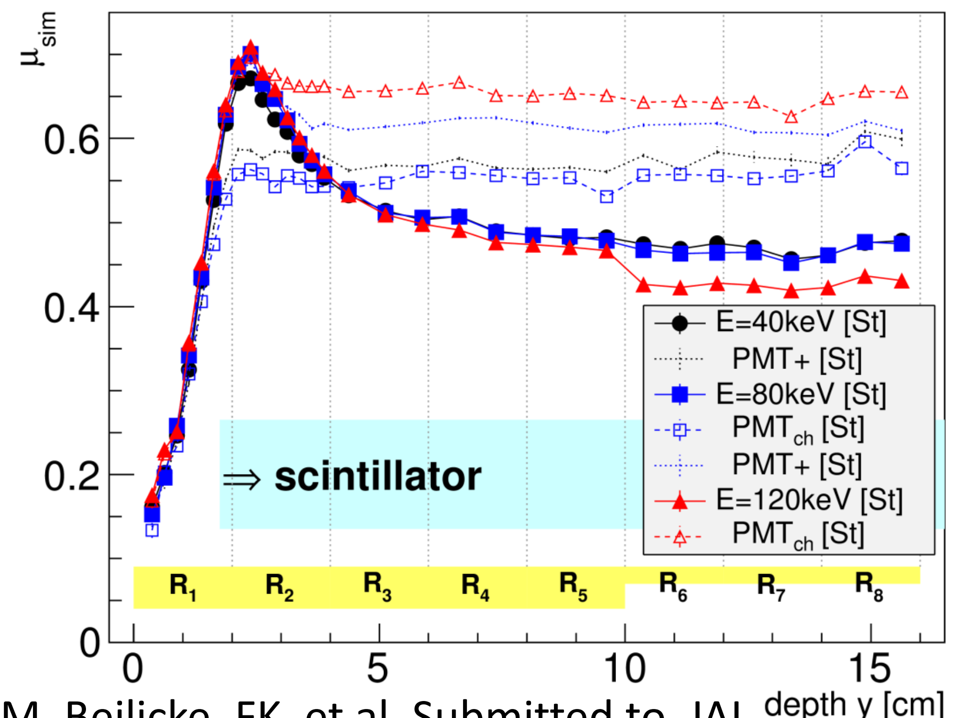

C103
C102



Highlights of *X-Calibur*

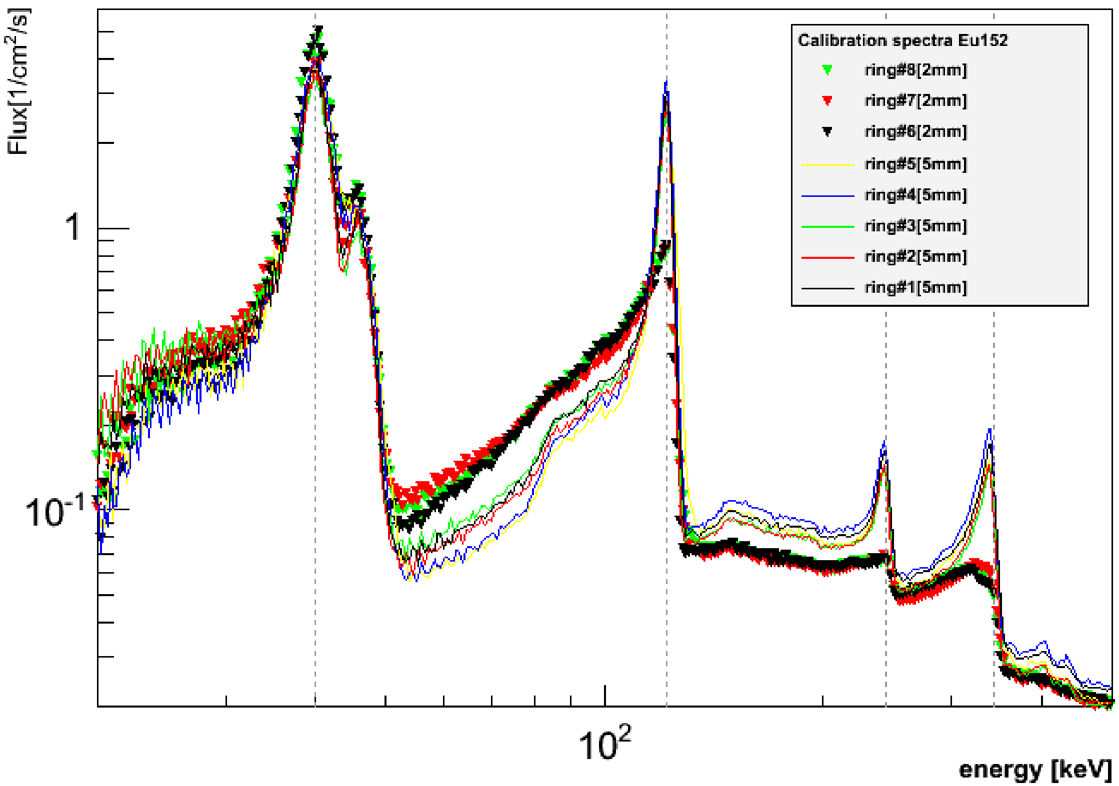
- Combines low-Z scatterer with high-Z detector.
- Energy range 25 – 60keV.
- High efficiency
  - Almost all photons hit the scintillator;
  - 90% of scattered photons are detected.
- Modulation factor close to limit set by Compton scattering.
- Controlled systematics through rotation of detector at 2rpm.
- Active and passive shielding against background.





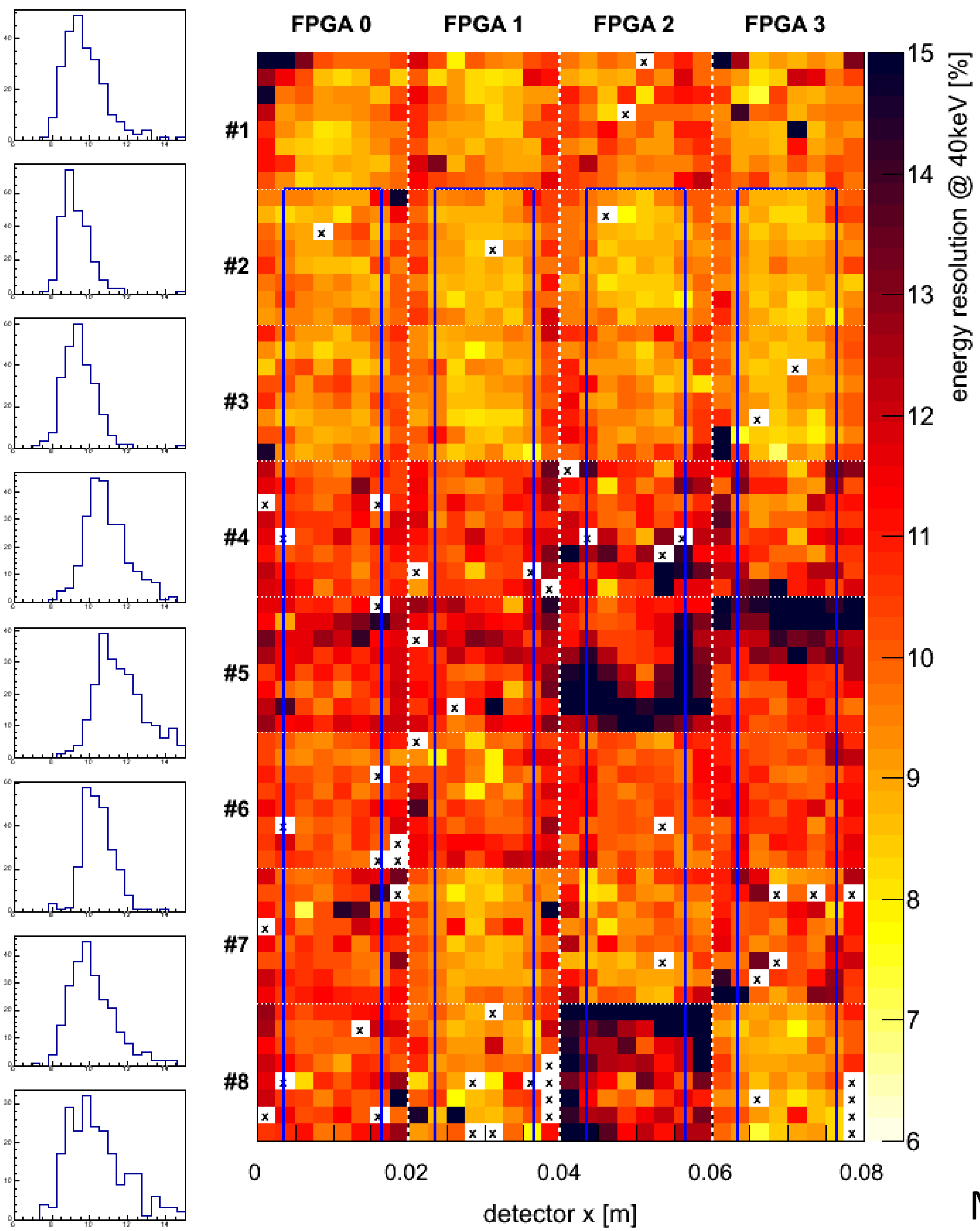
M. Beilicke, FK, et al. Submitted to JAI

Energy calibration



- Calibrate CZT detectors with Eu^{152} source
  - Pixel-by-pixel;
  - ~4keV FWHM @ 40keV;
  - >97% good channels;
  - Threshold optimization.
- Left figure: 1 spectrum per detector ring
  - Compare 5mm vs 2mm detectors;
  - Tradeoff: resolution vs background rate.

Energy resolution



- Eu^{152} source above detector center.
- ~10% resolution (at 40 keV).
- Poorer at detector edges.
- **Best detectors placed where rates are highest.**

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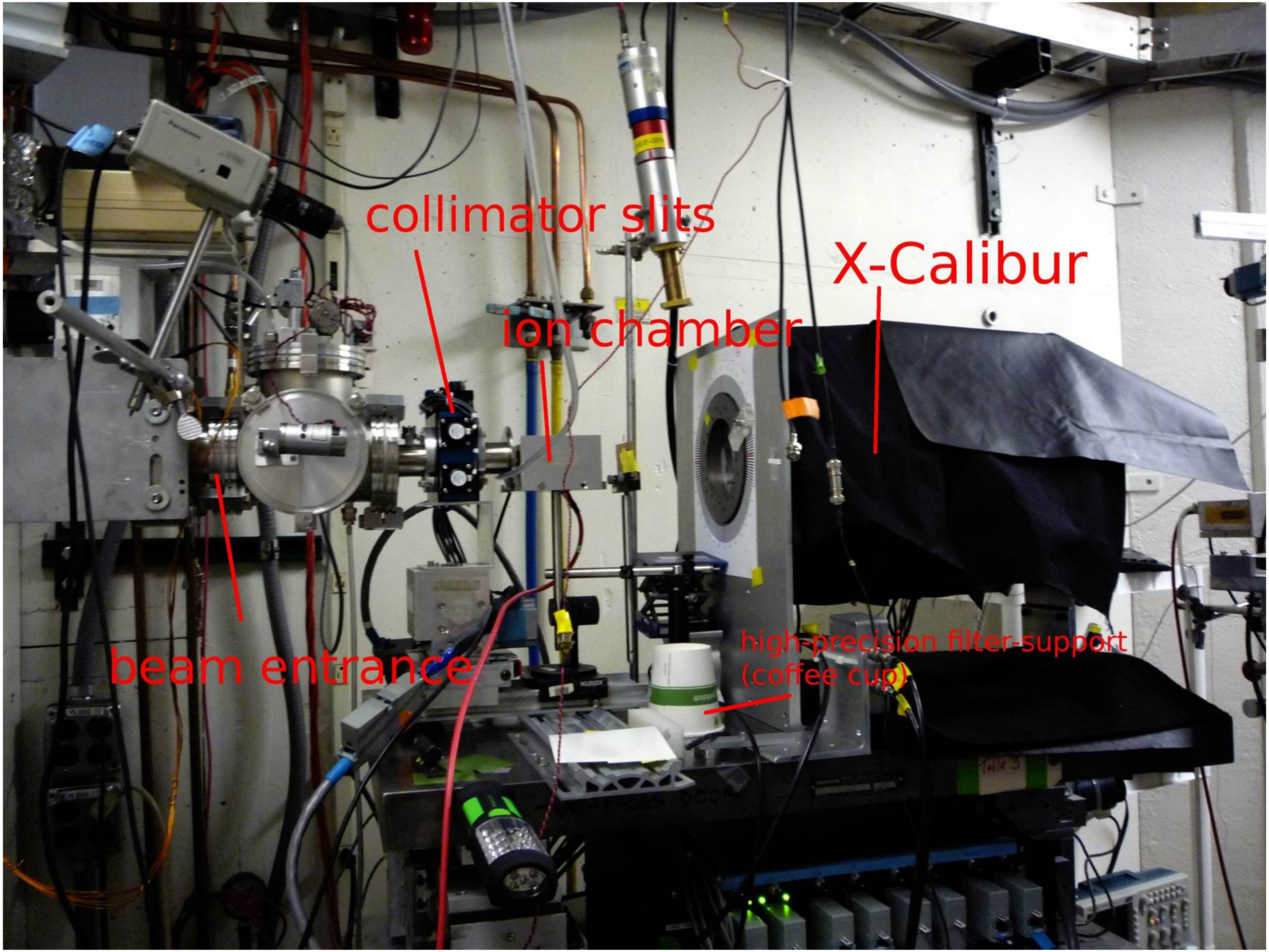
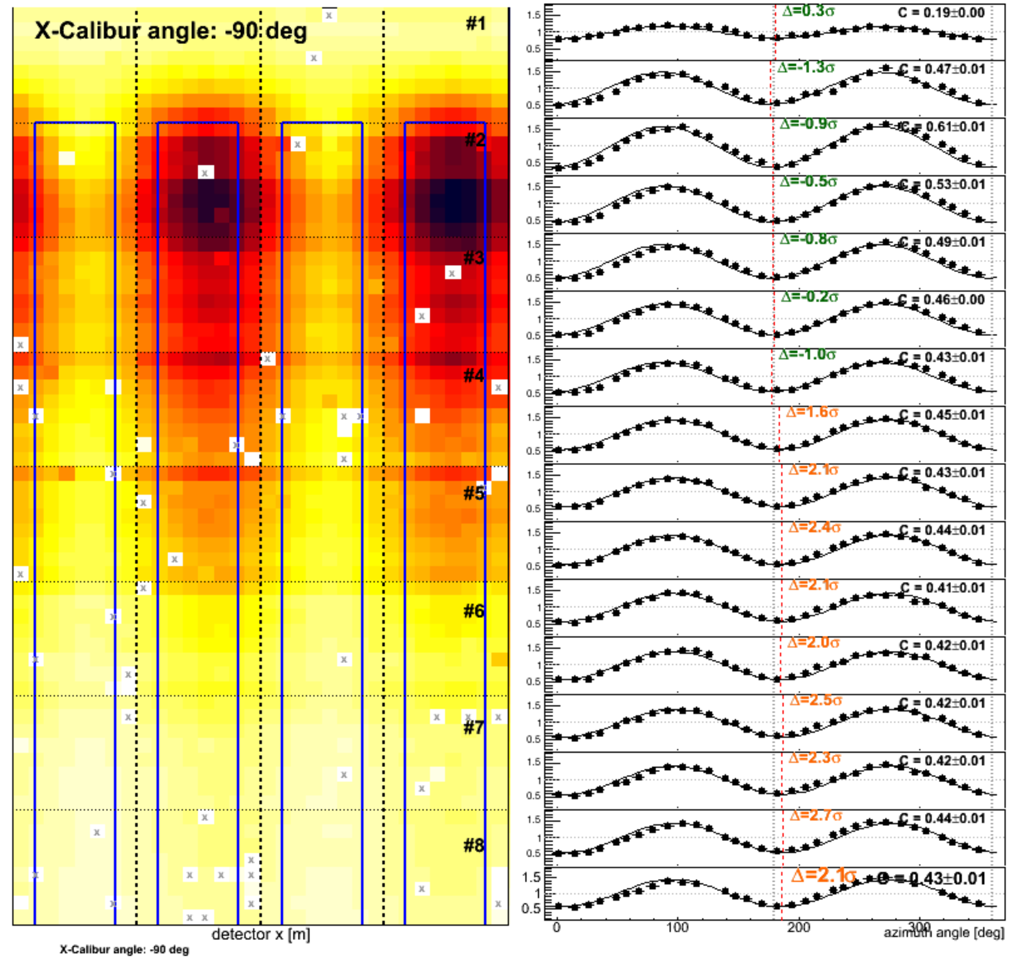
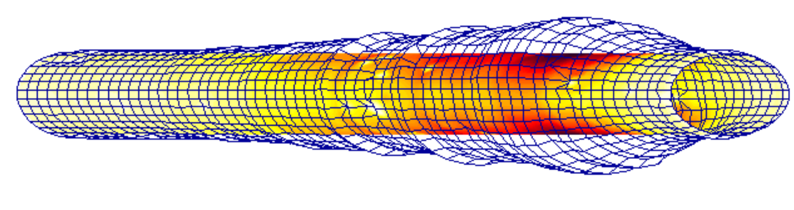
X-Calibur Tests at CHESS



Polarized Beam at CHESS

- Synchrotron beam at Cornell High-Energy Synchrotron Source (CHESS).
- ~90% polarized beam.
- Rotating detector.
- Polarization angle and fraction well reconstructed.
- Determined Modulation Factor: μ = 0.45 … 0.6 depending on ring.





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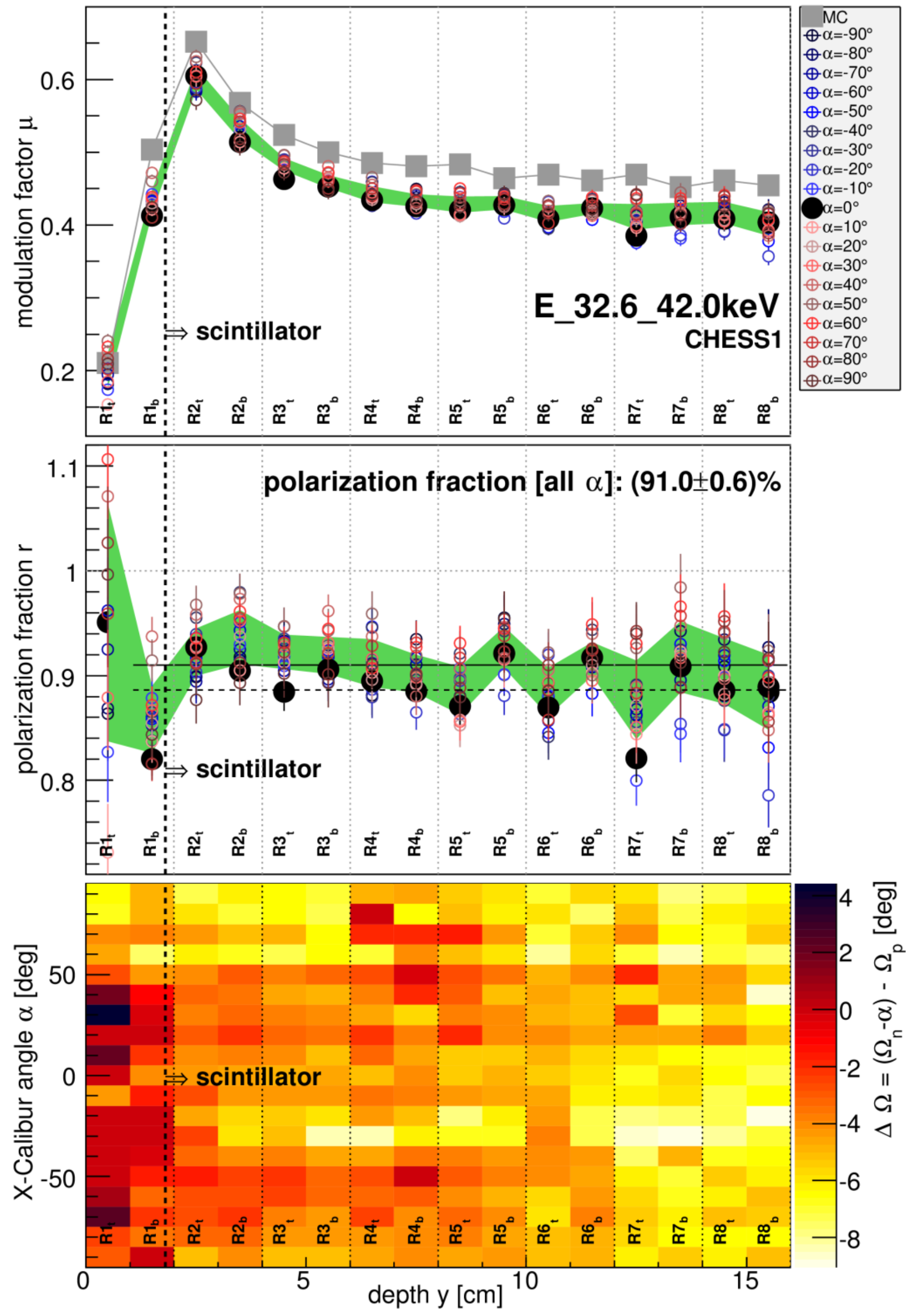
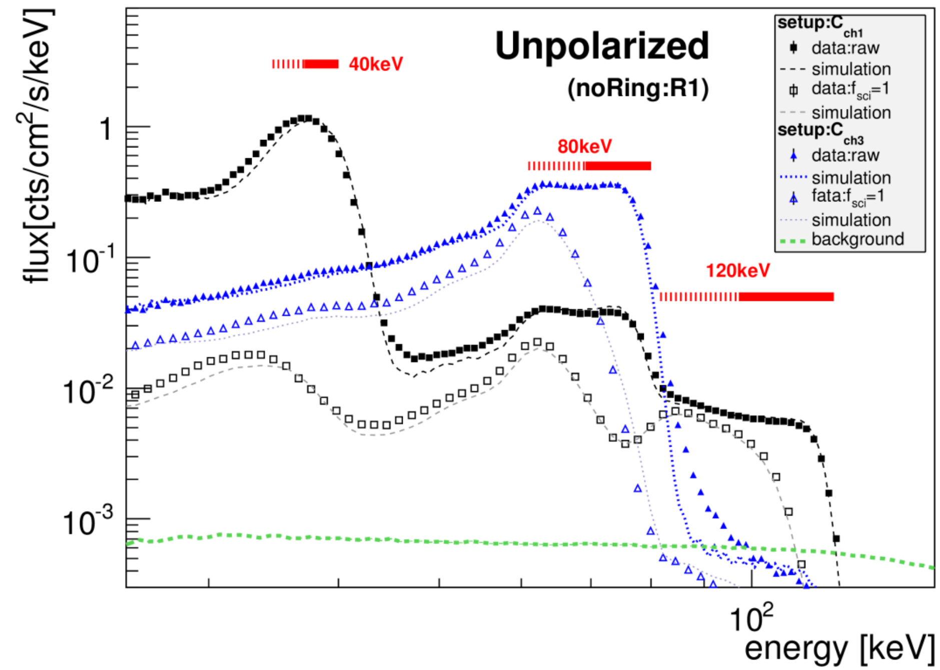
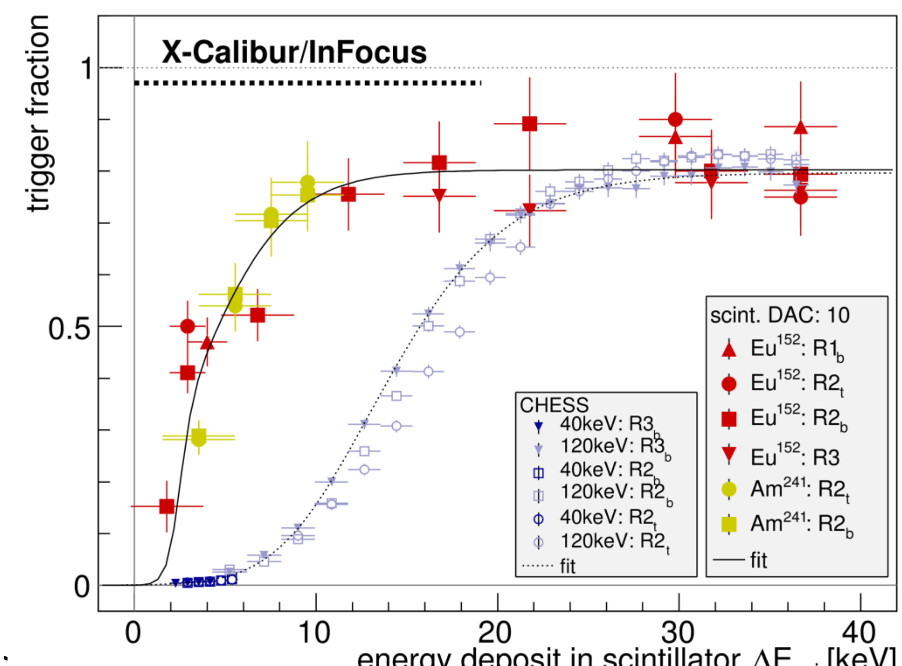


M. Beilicke, FK, et al. Submitted to JAI

CHESS Tests

- Bragg reflection ⇒ Lines at 40keV, 80keV, and 120keV.
- Known energy loss in scintillator ⇒ Determine scintillator threshold.
- Optimized after CHESS run by increasing pre-amp gain.
- Does not reach 1 probably due to contamination from direct hits.

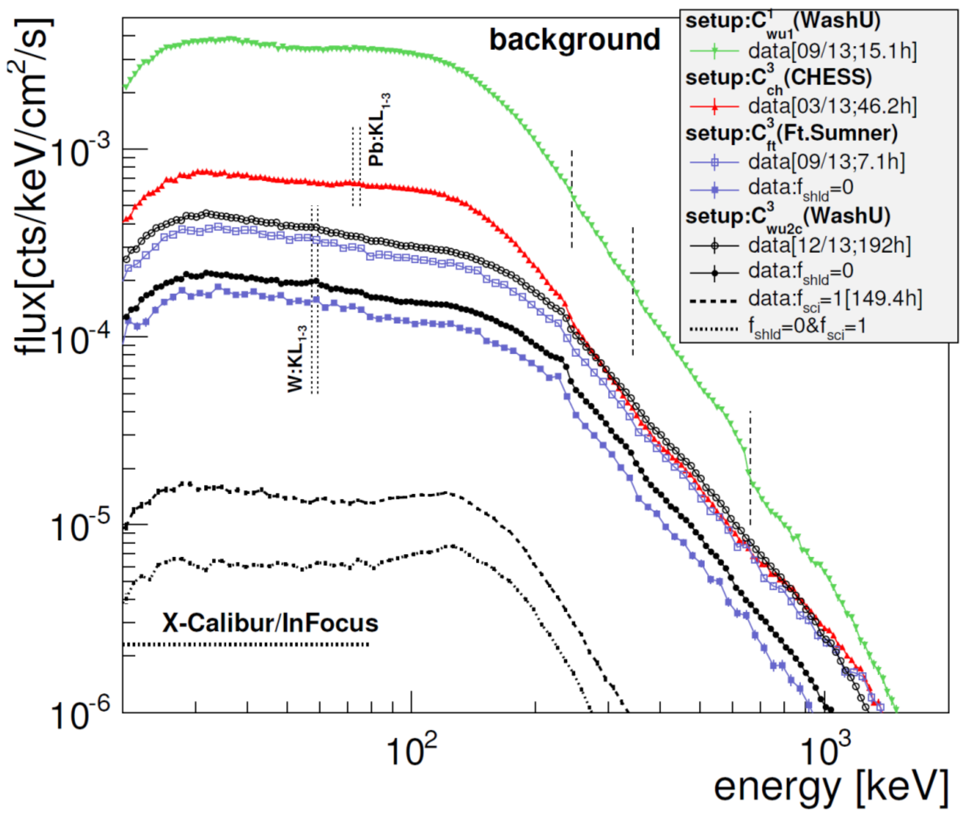




M. Beilicke, FK, et al. Submitted to .

Background Suppression

- Three levels of background suppression
  - Passive shielding;
  - Active CsI(Na) shield;
  - Coincidence between CZT and scintillator.
- Overall reduction of background 2½ orders of magnitude.



Data Analysis with Stokes Parameters

- Calculate for each event ($\chi_k = \alpha_k - 90°$):

$$q_k = \cos 2\chi_k$$
$$u_k = \sin 2\chi_k$$

- Then:

$$Q = \sum_{k=1}^{N} q_k$$
$$U = \sum_{k=1}^{N} u_k$$

- And:

$$p = \frac{2}{\mu}\frac{\sqrt{Q^2 + U^2}}{N}$$
$$\chi = \frac{1}{2}\operatorname{atan}\left(\frac{U}{Q}\right)$$

Data Analysis with Stokes Parameters

- Q and U normally distributed ⇒ Statistics straight-forward.
- Additivity: backgrounds can easily be subtracted.
- Re-derived well-known formula for MDP and best case for background observation

$$\mathrm{MDP} = \frac{4.29}{\mu\sqrt{N}} \qquad \mathrm{MDP} = \frac{4.29}{\mu\, R_\mathrm{S}}\sqrt{\frac{R_\mathrm{BG} + f_\mathrm{off} R_\mathrm{S}}{(1 - f_\mathrm{off}) f_\mathrm{off} T}}$$

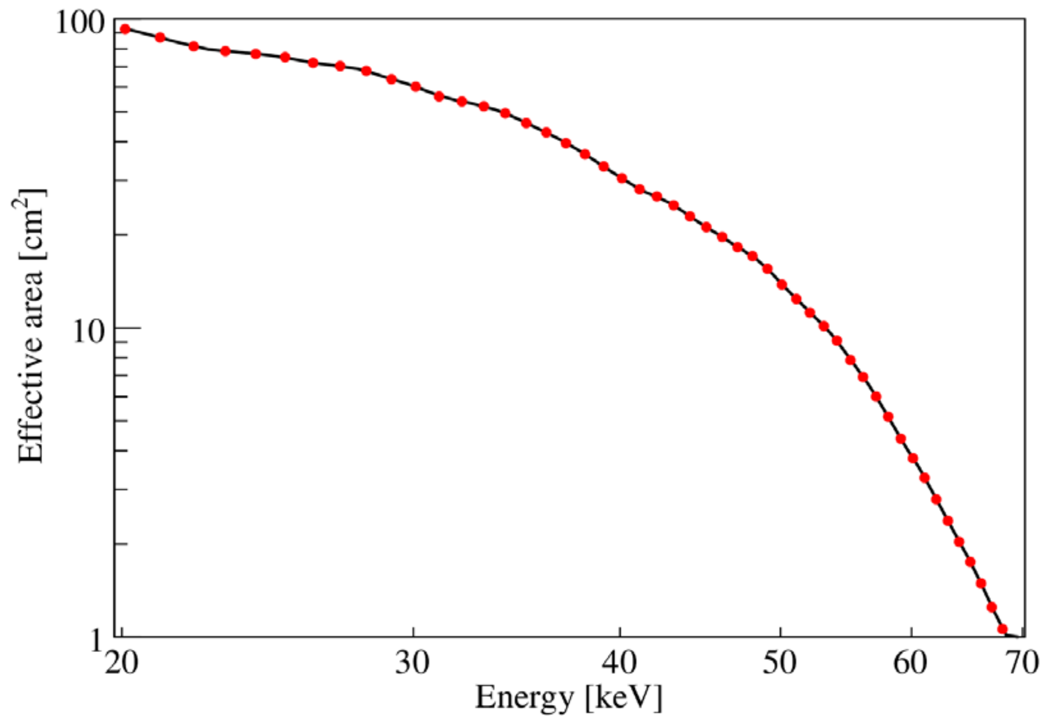
- Approximate expressions for uncertainties of p and χ:

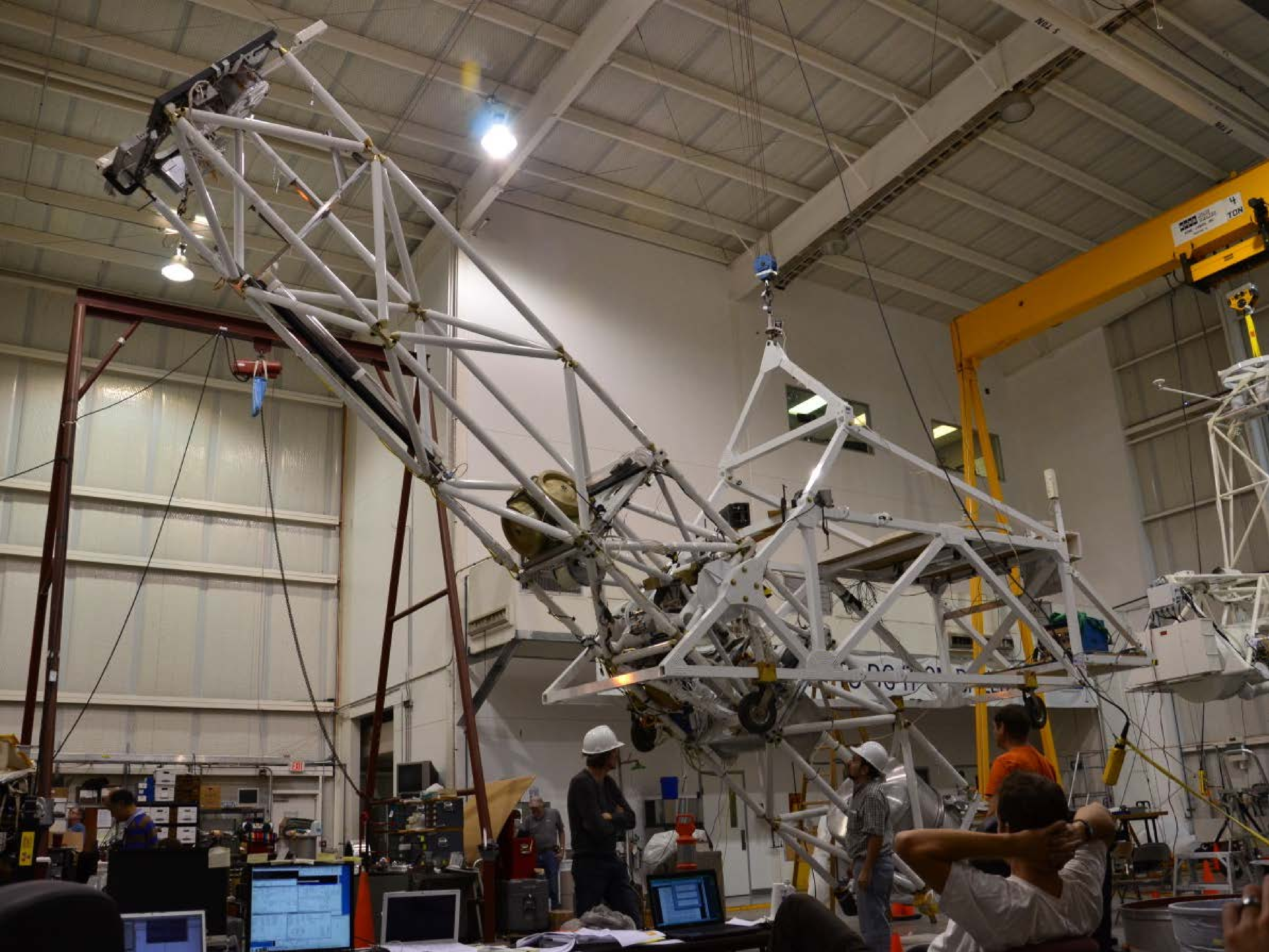
$$\sigma(p) \approx \sqrt{\frac{2 - p^2\mu^2}{(N-1)\mu^2}} \qquad \sigma(\chi) \approx \frac{1}{p\,\mu\sqrt{2(N-1)}}$$

- More details in FK, Clark, Beilicke, Krawczynski. About to be submitted to APh. Look on arXiv in a few days.

The InFOCuS Telescope

- Truss only connected to gondola through high-pressure ball joint.
- Pointing controlled through three reaction wheels.
- Fully inertial pointing system
  - Stability: 9” (alt) and 20” (az).
- Wolter-type grazing incidence X-ray mirror
  - 8m focal length;
  - 1-100cm² effective area.

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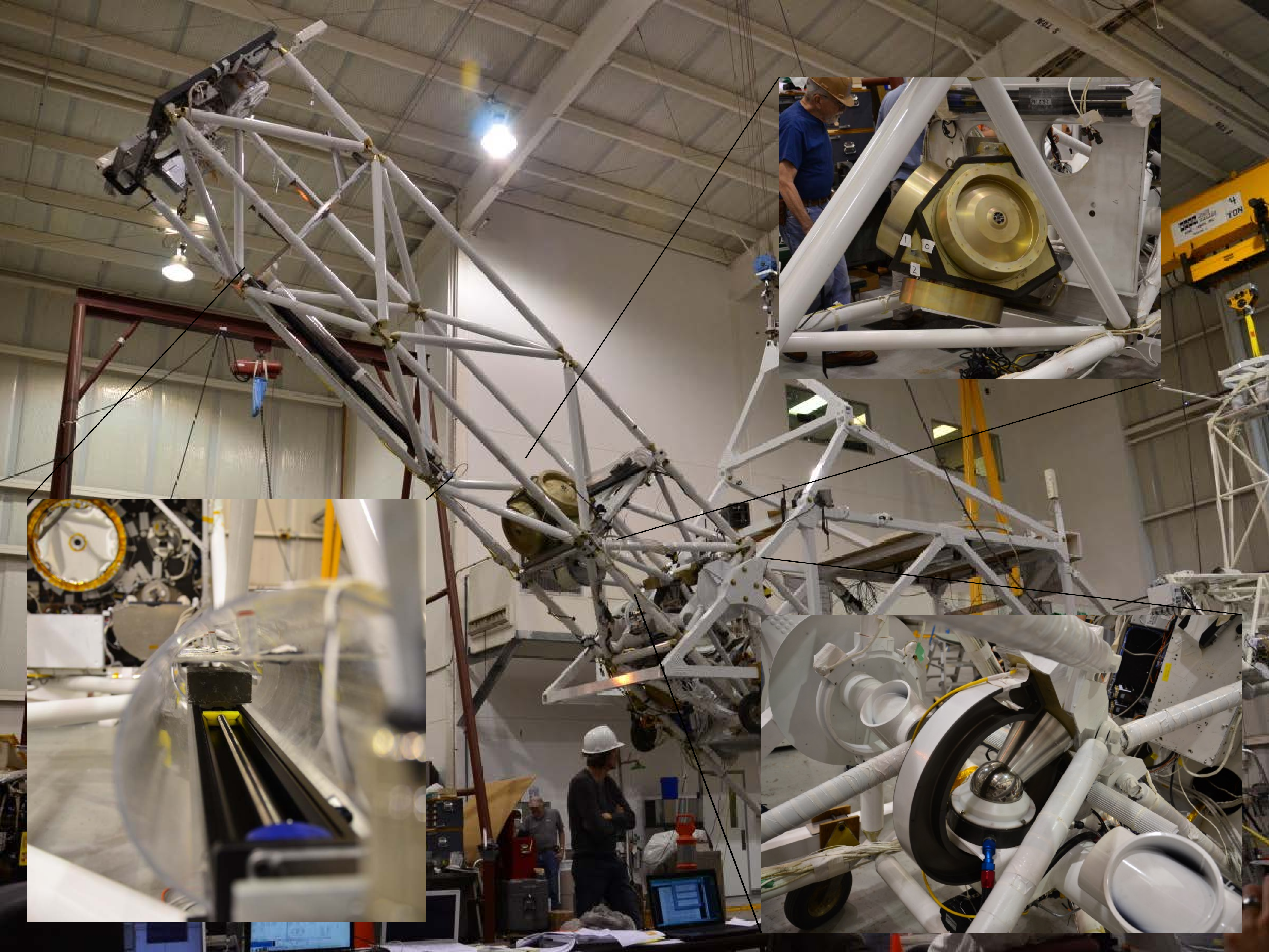
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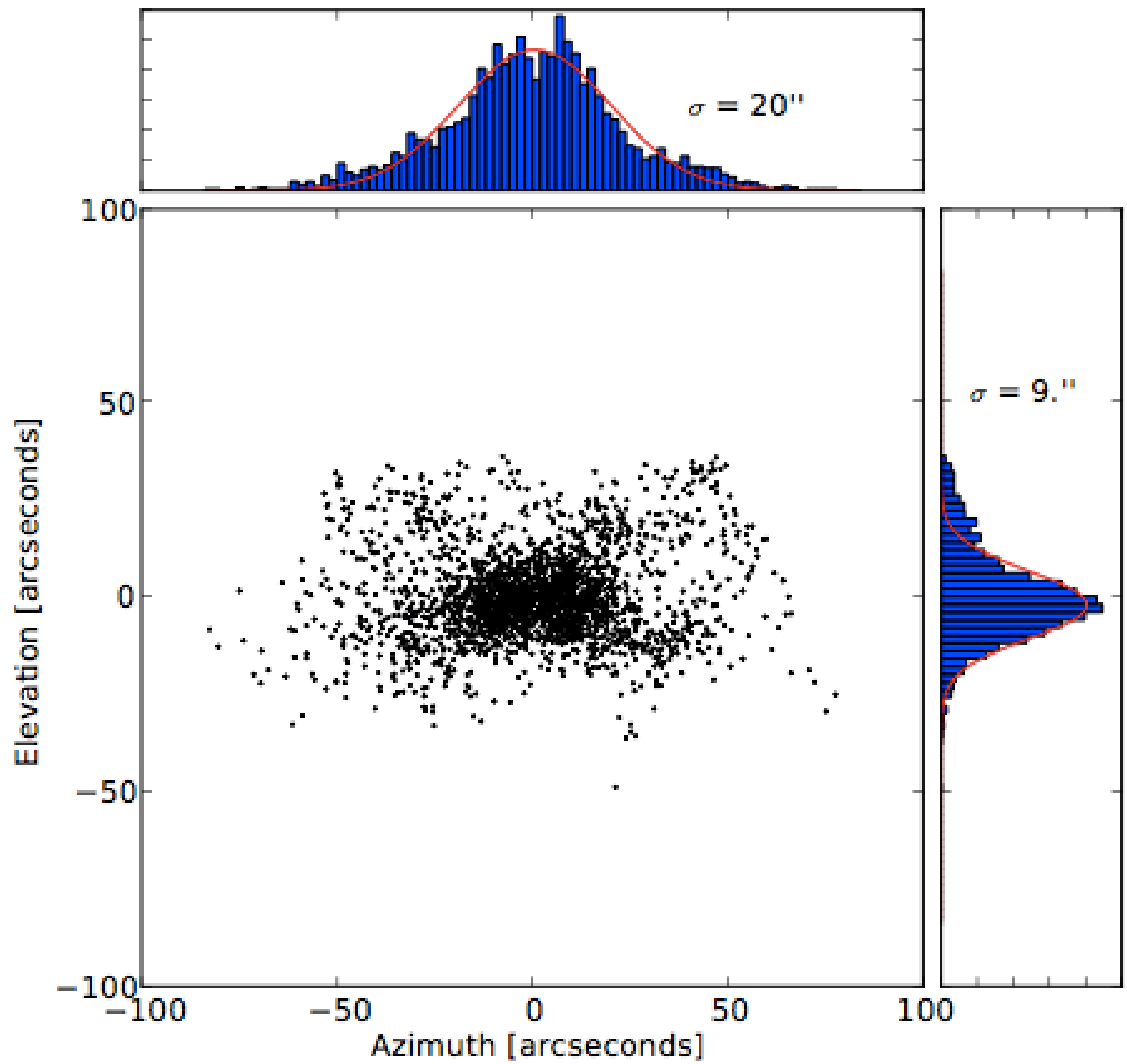
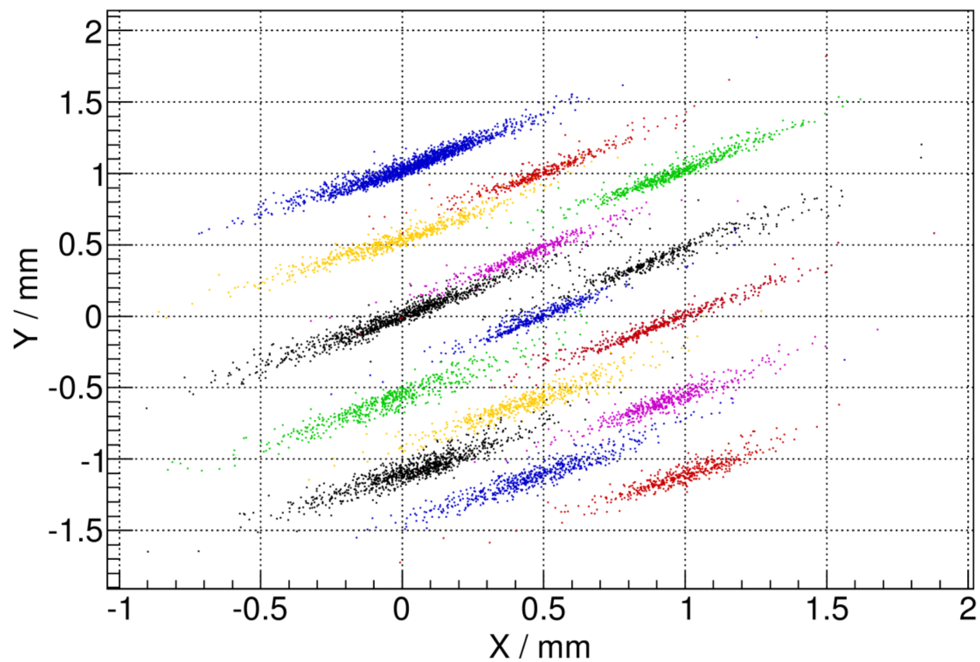
InFOCuS X-ray Telescope Performance

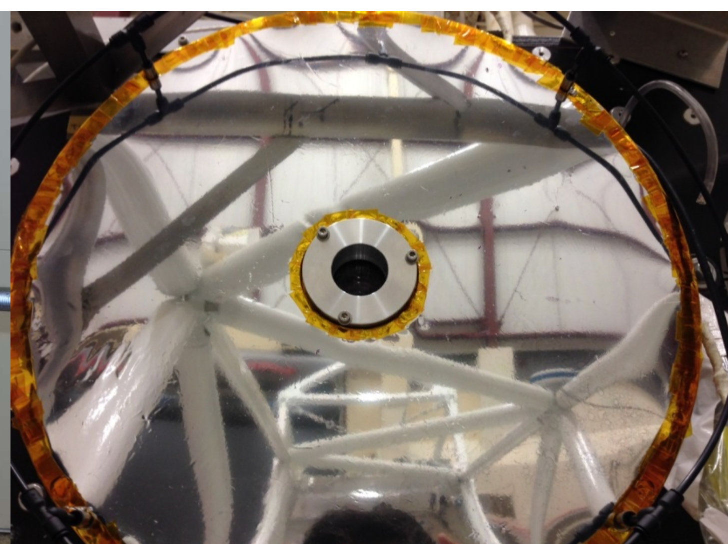
- Pointing accuracy:
  - 9” in elevation
  - 20” in azimuth
- System achieves projected performance.
- Exceeds requirements for X-Calibur.



Monitoring Focal Spot

- Alignment monitored by camera in mirror center looking back.
- Disc with 16 LEDs mounted to PV entrance window.
- Beam focal spot monitored with <0.5mm precision.





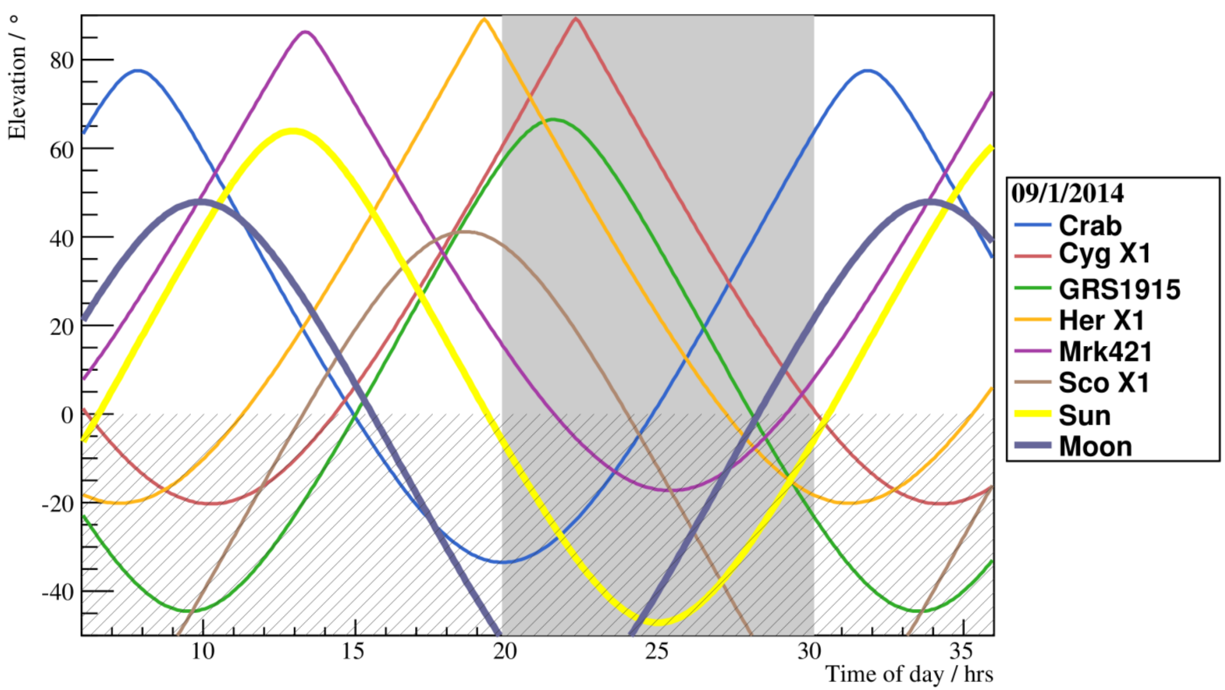
Current Status

- Currently preparing for 1-day flight from Ft. Sumner (NM).
- X-Calibur/InFOCuS electronics fully integrated.
- Pointing tests of the complete system in progress.
- Finalizing thermal shields.
- All work on schedule.
- Projected flight-ready date around September 6.
- Best time window for flight:

  Second half of September.

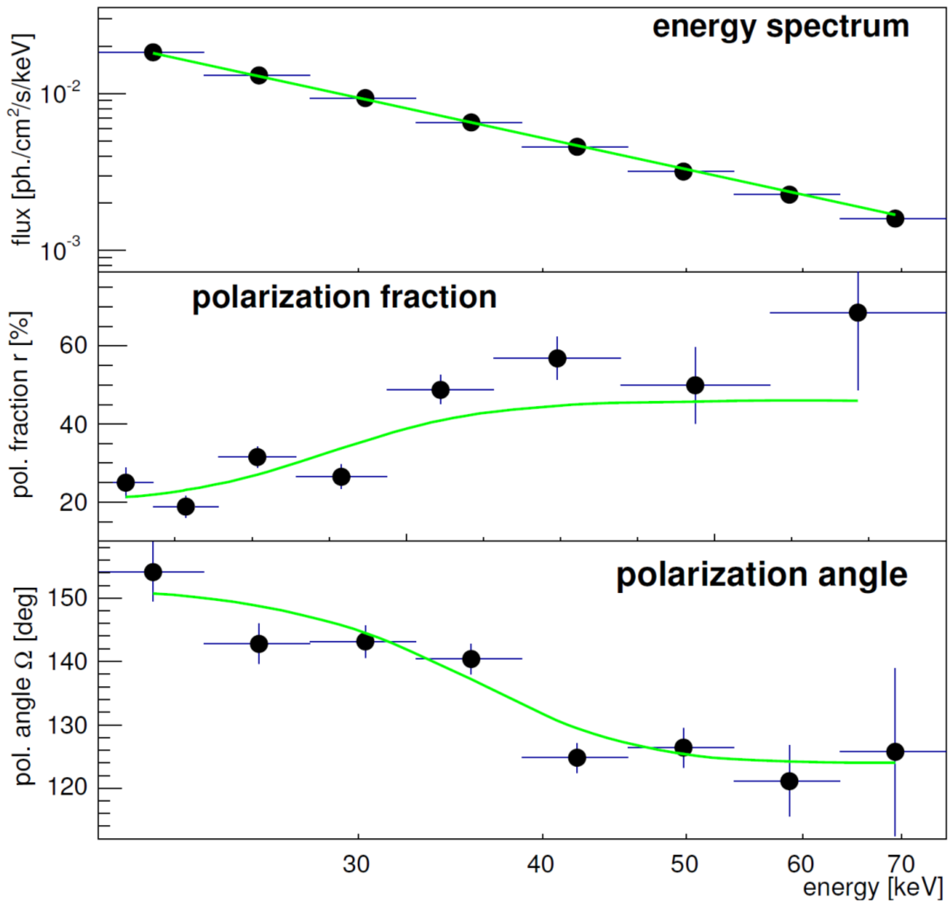
The 2014 Ft. Sumner Campaign

- 1-day flight from Ft. Sumner, New Mexico.
- Prove polarimeter functionality in flight.
- Targets:
  - Crab pulsar and nebula
  - Sco X-1
  - Cyg X-1
  - GRS 1915+105
  - Her X-1
  - Maybe Mrk 421



Simulated 1-day Crab observation

- Flux and energy spectrum of Crab.
- Polarization fraction and direction as observed by OSO-8 at low energies and INTEGRAL at high energies.
- Observation time 5.6 hours.
- Using InFOCuS effective area and absorption at 130kft float.



Target Candidates

Source	Class	Flux [mCrab]	Obs. Time [hrs]	MDP [%]
Crab	P & PWN	1000	6	5
Sco X-1	Accreting NS	810	6	7
Her X-1	APP	300	5	16
GRS 1915+105	BBH	500	4	11
Cyg X-1	BBH	923	3	7

- Crab, Cyg X-1, Sco X-1: mean 14-150keV fluxes from Swift BAT 58 month survey
- Her X-1, GRS 1915+105: flare flux levels

X-Calibur Broadband Scattering Polarimetry

Proposal for the Upcoming SMEX Announcement of Opportunity.

Krawczynski & Harrison et al.

Science Team

Seniors: F. Aharonian. M.G. Baring,
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A. Ingram, H.S. Krawczynski, M. Lyutikov,
T. Maccarone, J.M. Miller, J.C. McKinney,
R. Narayan, F. Ozel, D. Psaltis, D. Stern.

Post-Docs & PhD Stud.: R.Amini,
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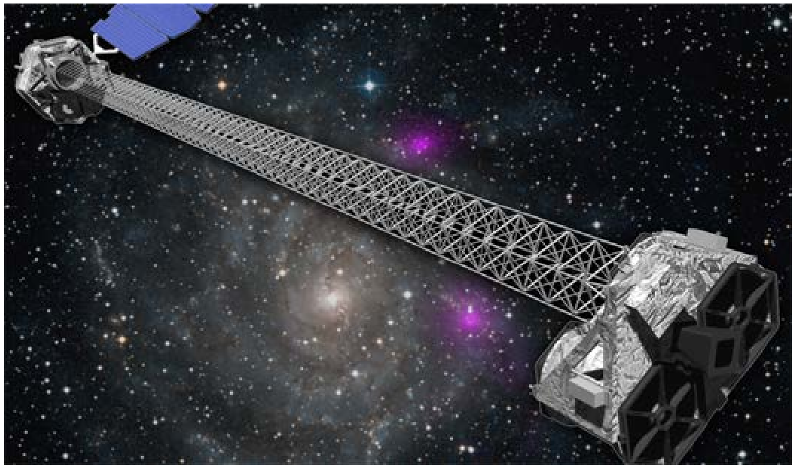
A. Zajczyk.

X-Calibur Broadband Scattering Polarimetry

NuSTAR Technology



X-Calibur Scattering Polarimeter Configuration

- Design maximizes ***NuSTAR heritage*** and minimizes cost and schedule risk.
- Main difference to NuSTAR: ***reconfigured*** detector configuration and added scattering element for ***scattering polarimetry*** (soft and hard X-Rays).
- ***Sensitivity:*** broadband polarimetry with ~1% pol. Sensitivity for ~mCrab sources.

Summary and Outlook

- X-Calibur is a scattering polarimeter that achieves O(100%) efficiency over most of its energy range.
- Low backgrounds and good control of systematic errors.
- Polarimeter has been beam-tested at Cornell High-Energy Synchrotron Source.
- We will fly the polarimeter in the focal plane of the InFOCuS X-ray telescope.
- Telescope has been upgraded for fully inertial pointing.
- First one-day flight from Ft. Sumner: in a few days from now!
- Targets:
  - Crab (energy and phase-resolved polarimetry!)
  - GRS1915+105 & Cyg X-1 (binary BH systems)
  - Sco X-1 & Her X-1 (Accreting neutron stars)
- A proposal for a satellite-borne scattering polarimetry SMEX mission is in preparation.