Silicon strip detectors for FOXSI: The Focusing Optics X-ray Solar Imager

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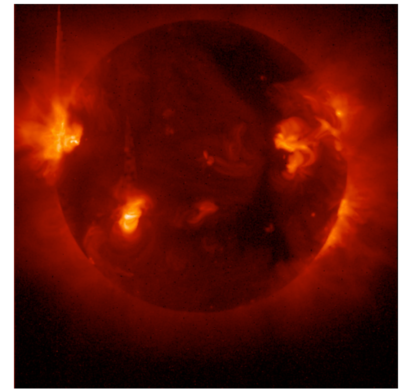
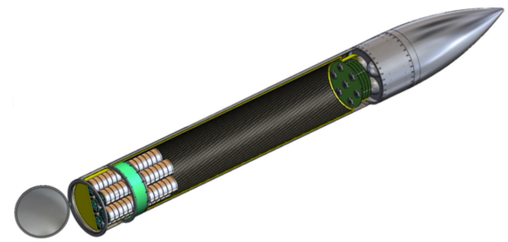
6 Stanford University

Outline

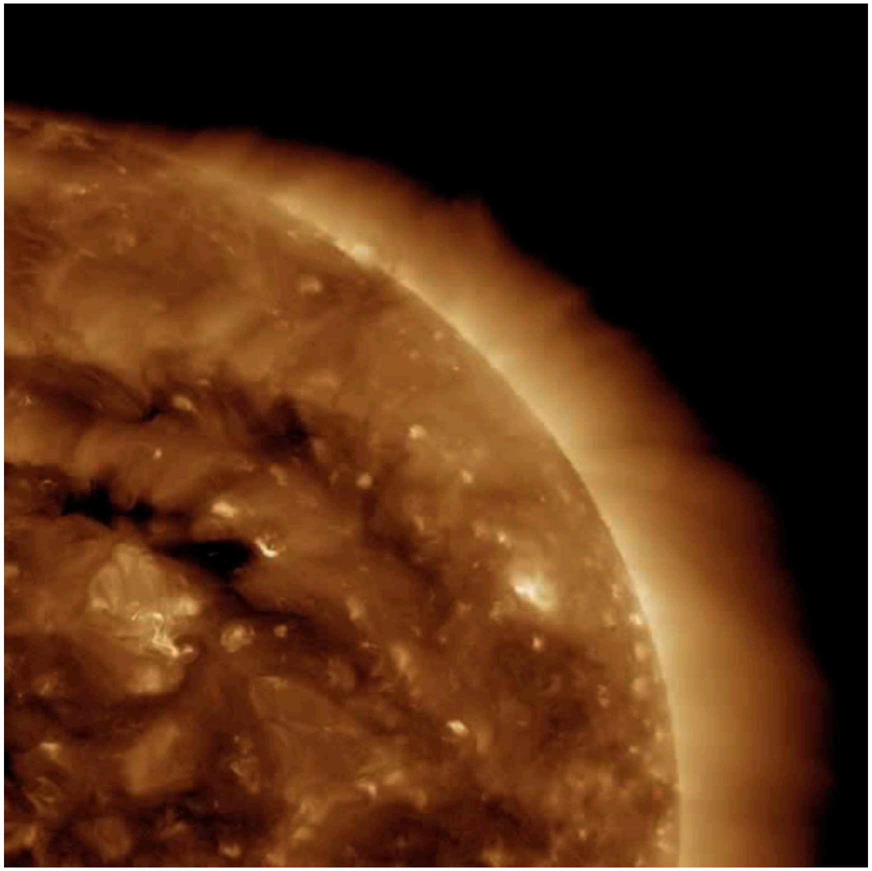


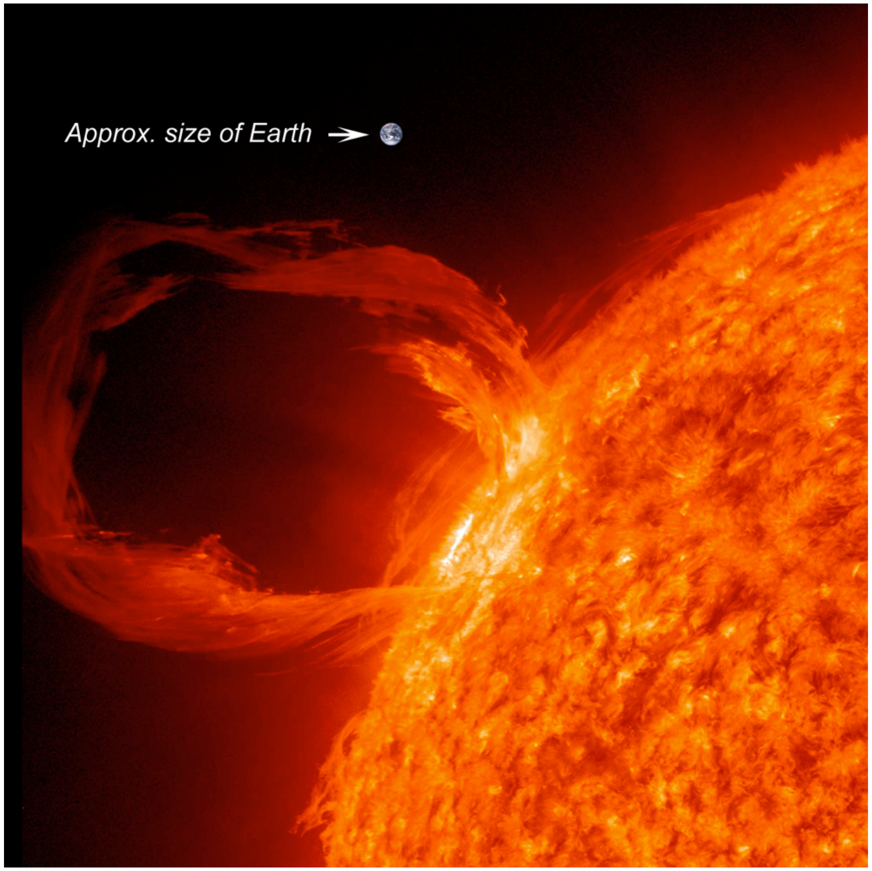
- Motivation for FOXSI
- The FOXSI sounding rocket project



- FOXSI's detector system
- Targets and plans

Introduction: Solar Flares





Extreme ultraviolet images of the Sun from the Solar Dynamics Observatory / Atmospheric Imaging Assembly

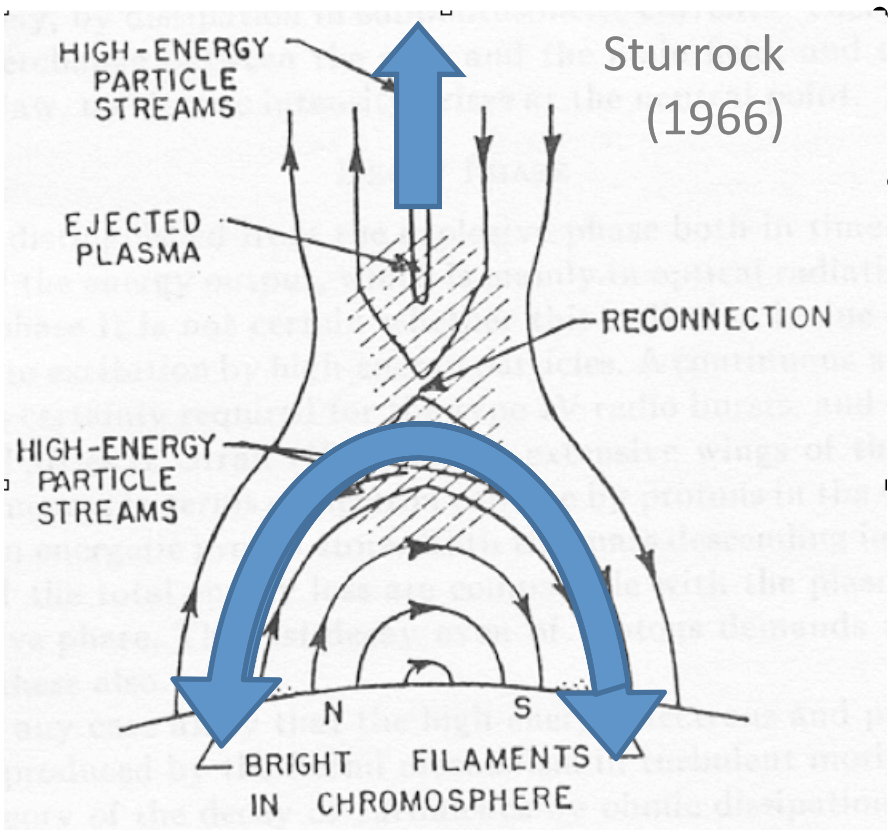
Introduction: Solar Flares

- Particle acceleration at the Sun: solar flares
  - Electrons accelerated up to hundreds of MeV
  - Ions accelerated up to tens of GeV
  - Total energy output: up to 10^{32} - 10^{33} ergs in 10-1000 sec
  - Some energy/particle flux reaches the Earth!

Unanswered questions…

- How/where do flares release energy?
- What is the source of the corona's high temperature?

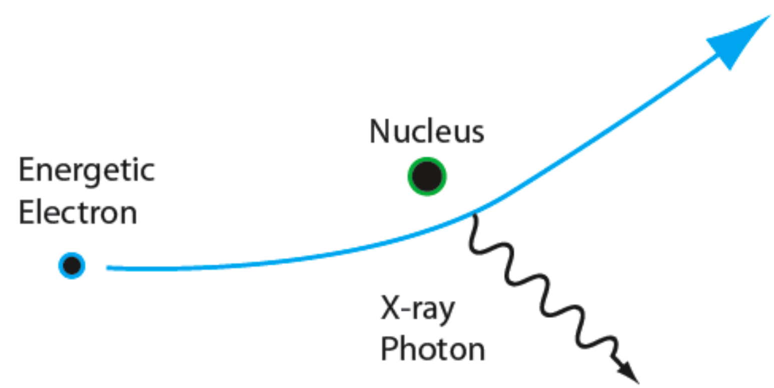
How / where does particle acceleration happen?



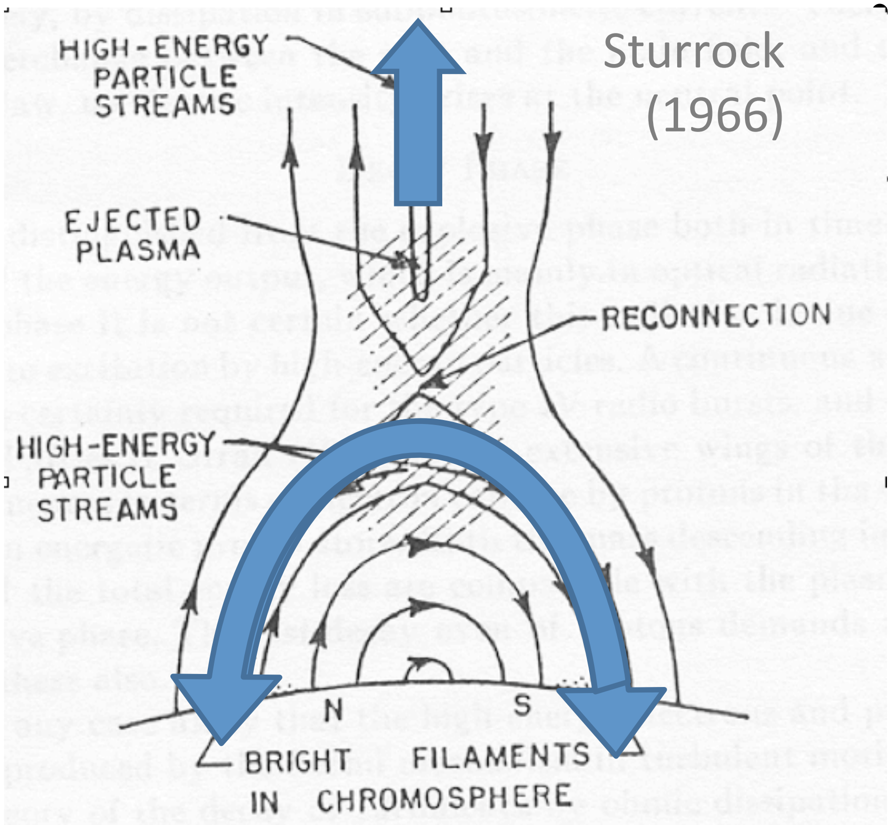
Energy stored in coronal magnetic field

Magnetic reconnection transfers energy into particles

- X-ray diagnostics: energetic e^- emit bremsstrahlung (thermal and nonthermal).
- Loop and footpoints are clearly seen.

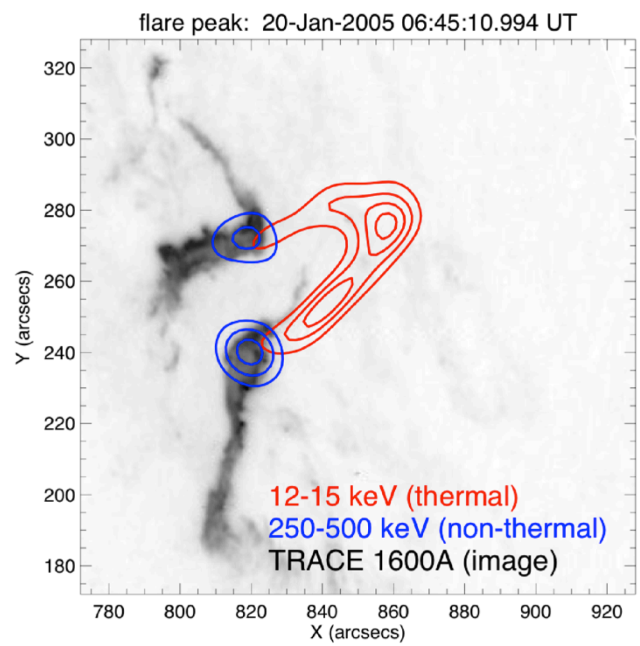


How / where does particle acceleration happen?



Energy stored in coronal magnetic field

Magnetic reconnection transfers energy into particles



- To further study this model we need **sensitivity** and **dynamic range**

What heats the corona?

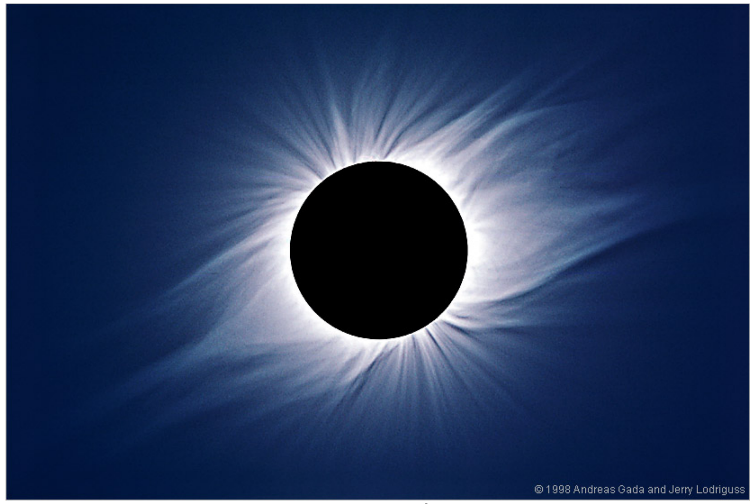
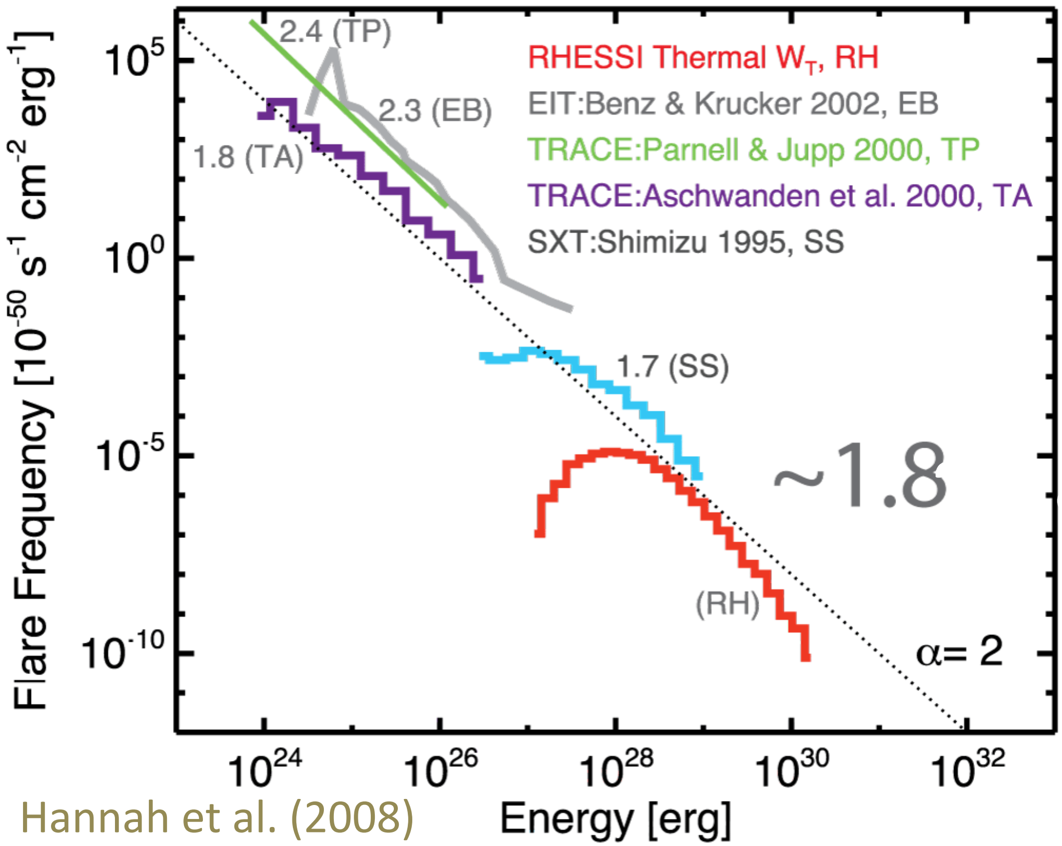


Photo: Andreas Gada / Jerry Lodriguss

- The temperature of the solar corona is 1-2 MK, up to ~20 MK or more during solar flares.
- The temperature of the photosphere is ~5800 K
- To sustain this temperature, the needed energy input is 10^5-10^7 erg cm^{-2} s^{-1} for quiet to active regions, respectively. (See Withbroe and Noyes, ARA&A, 1977)

Flare Heating?



Hannah et al. (2008)

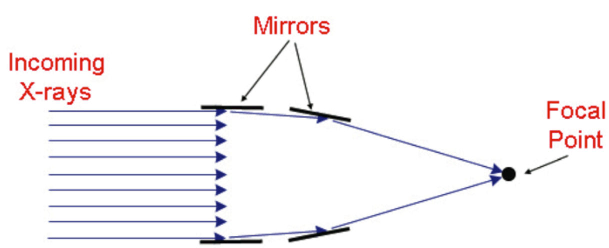
- Do flares provide enough energy to heat the corona?
  - Large flares? **No.**
  - Small flares? **Unknown**
- What is the shape of the frequency distribution at low energy scales?
- Are small flares similar to large flares?

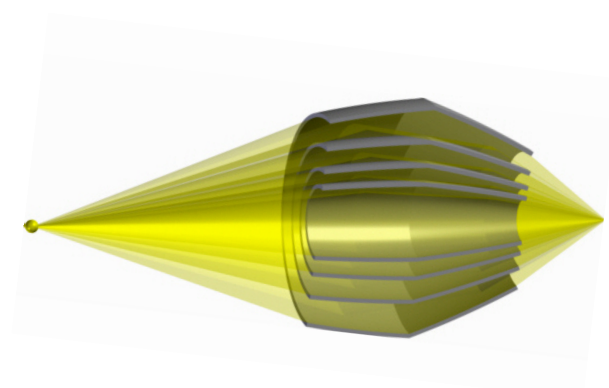
To answer these questions, better **sensitivity** is needed.

How to measure solar X-rays?

- Previous missions: **indirect imaging**
  - Ex. Reuven Ramaty High Energy Solar Spectroscopic Imager
  - Rotation modulation collimators

- FOXSI's approach: **focusing optics**
  - Small detector volume => reduced background => better sensitivity
  - Easier imaging reconstruction
  - Narrower point spread function => higher dynamic range.



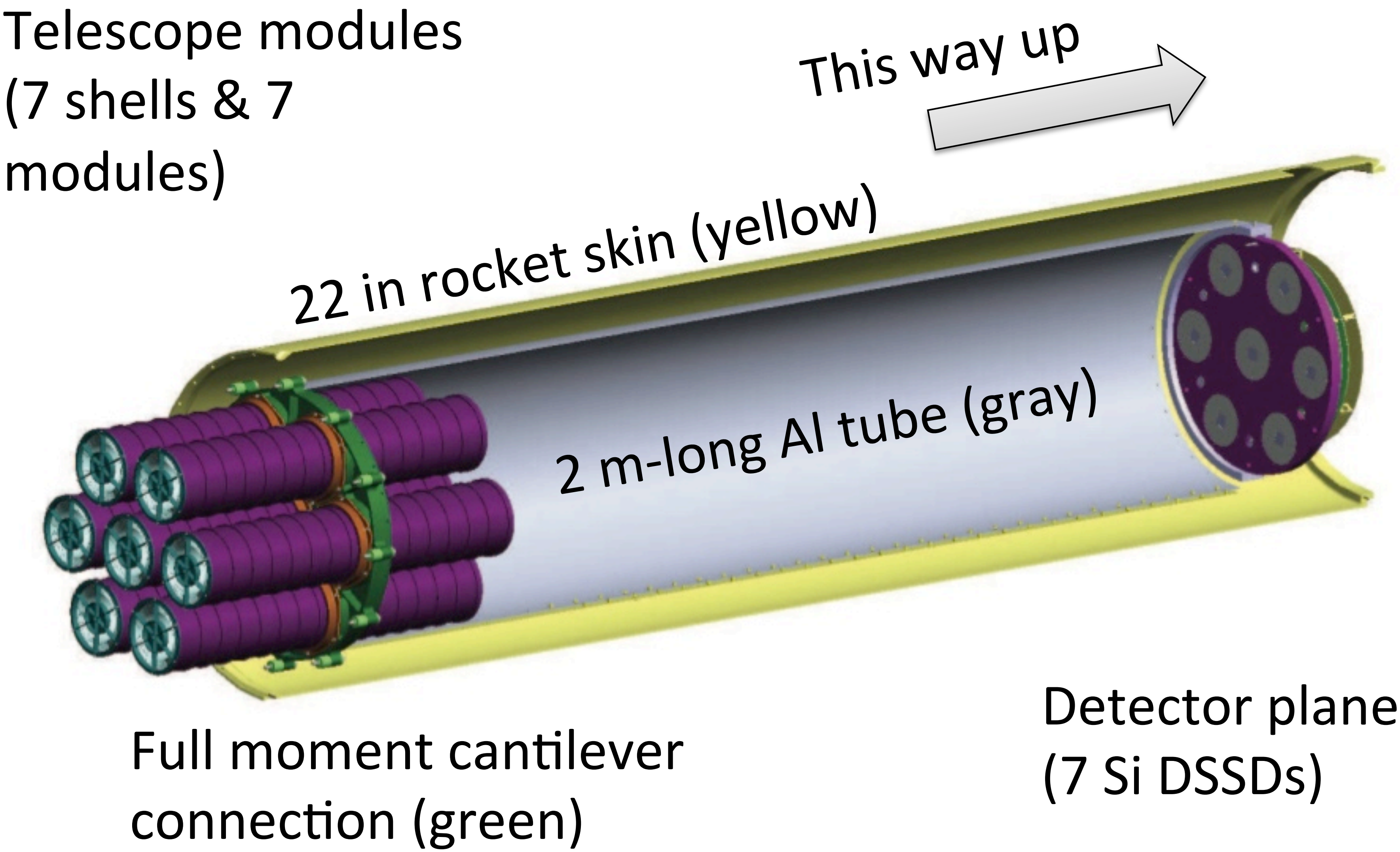


FOXSI

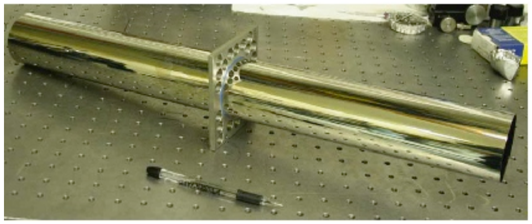
The **F**ocusing **O**ptics **X**-ray **S**olar **I**mager

- The FOXSI sounding rocket is funded under NASA *Low Cost Access to Space* program.
  - Launch late 2012, 15 minute flight
- Array of 7 optics modules focusing on 7 detectors
  - Replicated HXR focusing optics (NASA Marshall)
  - Double-sided silicon strip detectors (ISAS/JAXA)
- Optimized for 4-15 keV

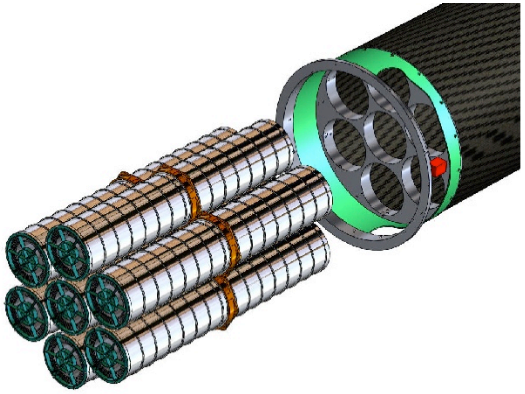
FOXSI Payload Overview



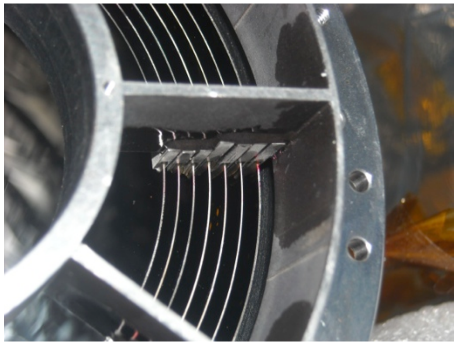
FOXSI Optics Details



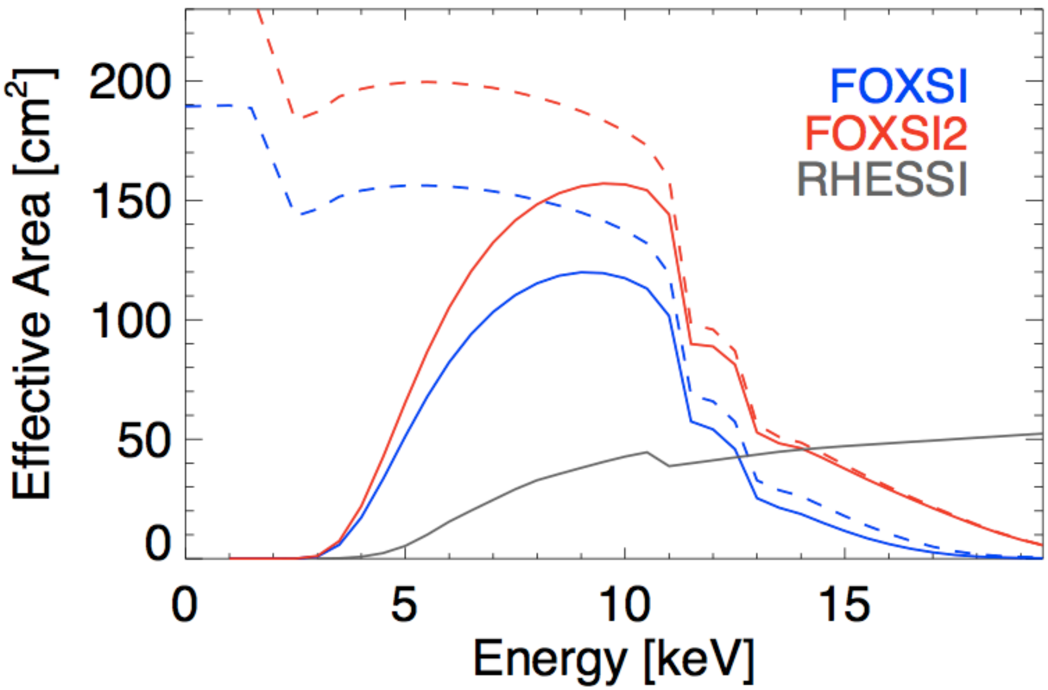
- Nested mirrors in Wolter-I geometry
- Produced at NASA/Marshall
  - Fast, low-cost replication technique



- Heritage
  - Astrophysics missions (Chandra, NuSTAR)
  - HERO balloon program
- Focal Length: 2 m
- 7 modules, 7 shells each
  - 3.8-5.1 cm radii
  - 60 cm length
  - 2m focal length



Effective area

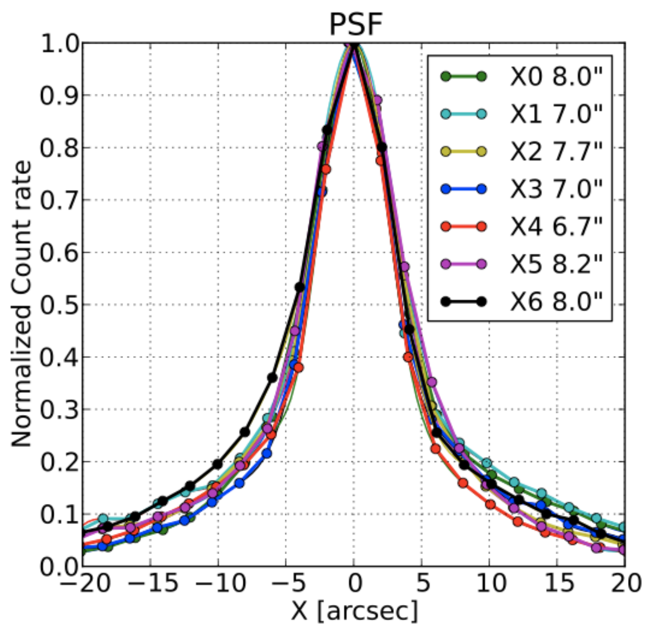


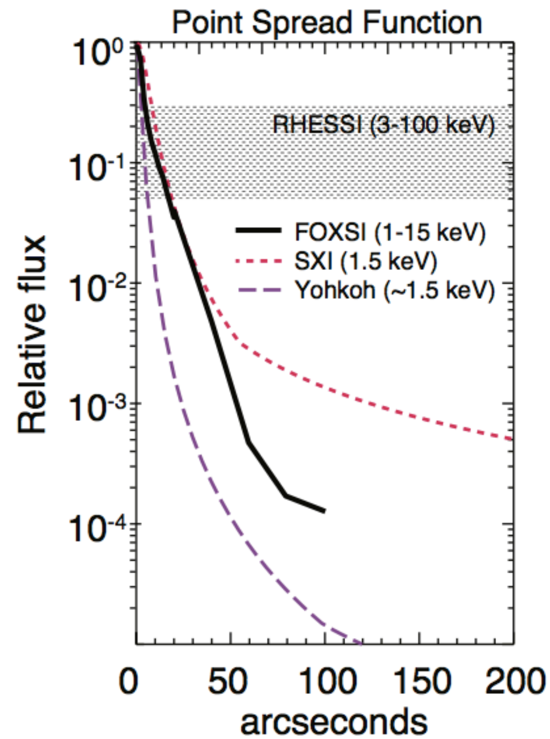
The dashed line represent the area provided by the optics. The effective area including thermal blanketing and detector response is also shown (solid lines).

- Blue = current
- Red = upgrade (~2014)

- FOXSI has **30x** the effective area of previous instruments (around 10 keV).

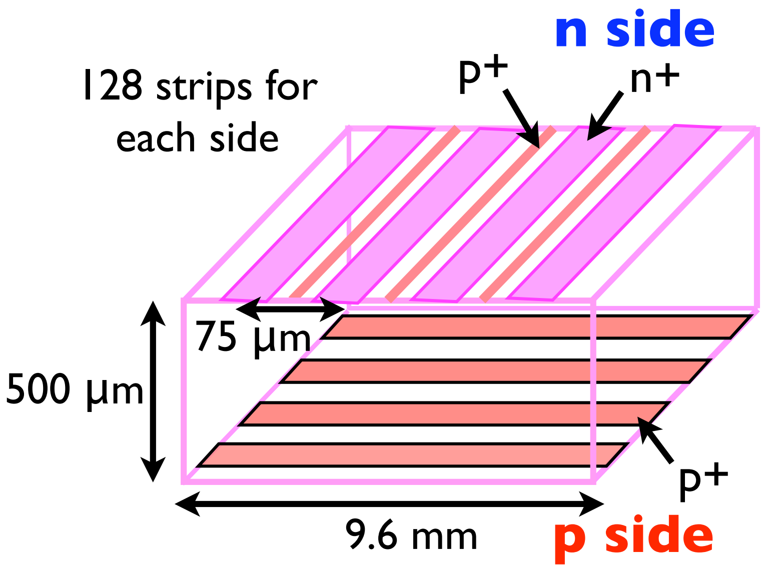
Point spread function

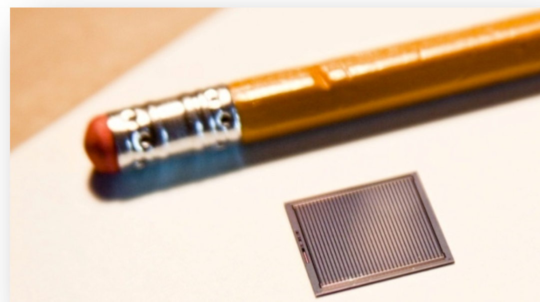


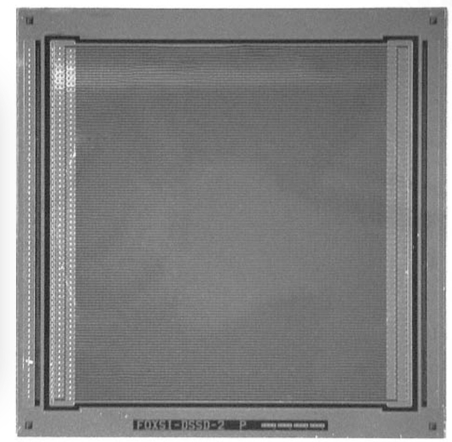


- FOXSI dynamic range:
  - Factor of 100-1000
  - 10-100 better than previous solar HXR observations (RHESSI).

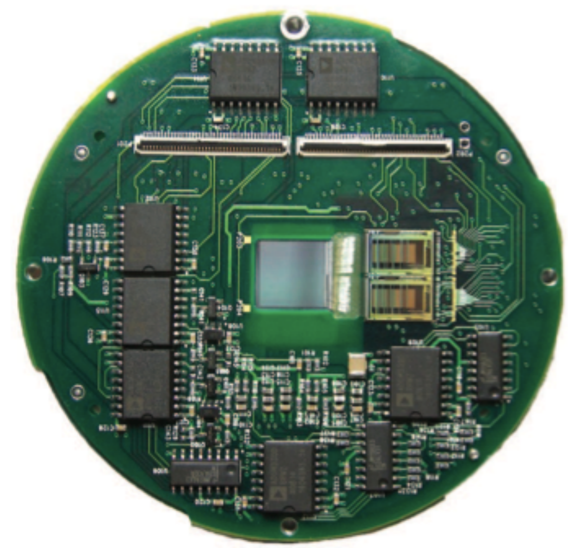
Detector system



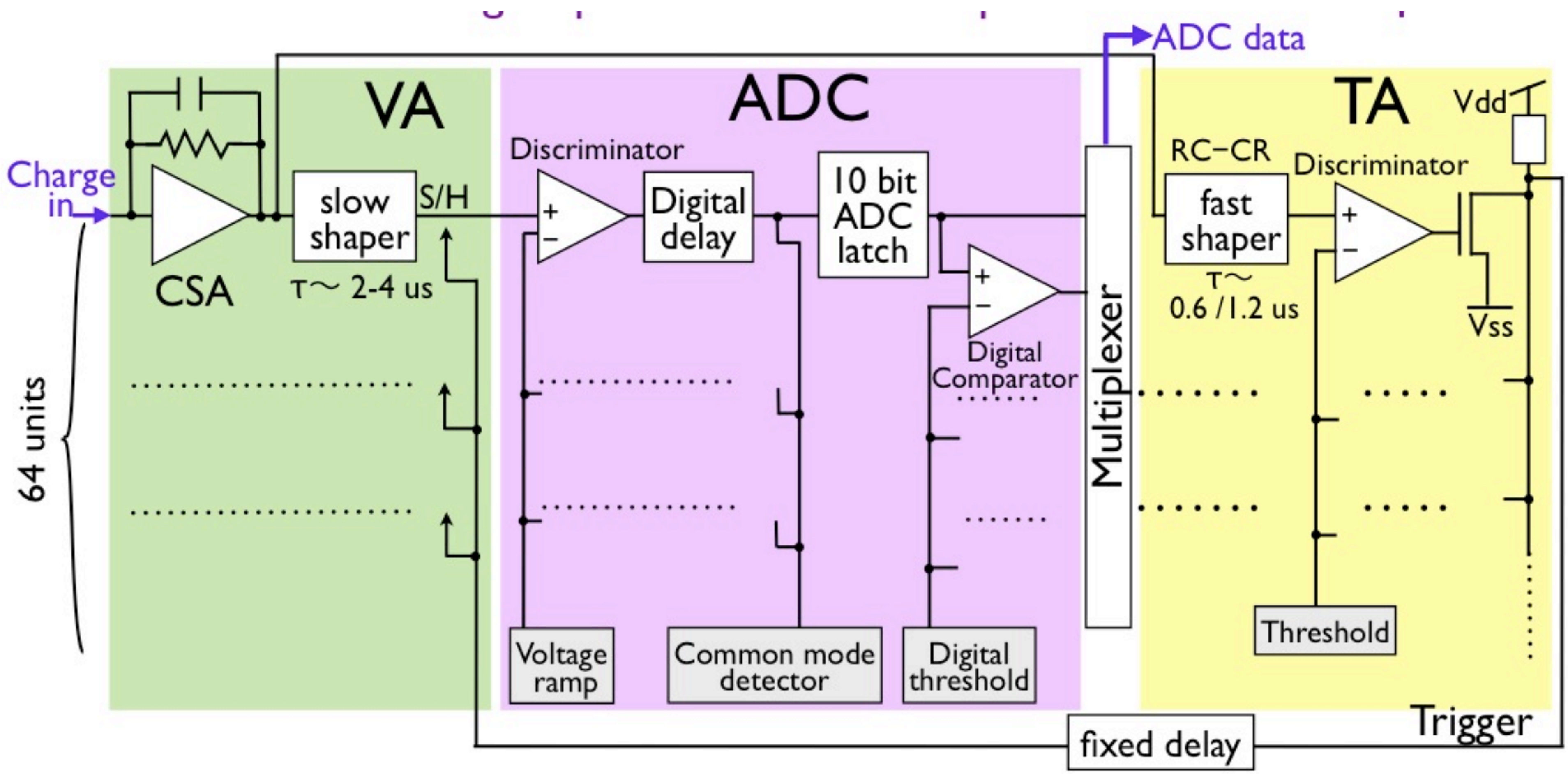




- Double-sided Si strip detectors
- Designed by Takahashi group at ISAS
- Fabricated by Hamamatsu Photonics
- 75 um pitch => ~8 arcseconds
- 128x128 strips per chip
- Array of 7: 1 detector per optic



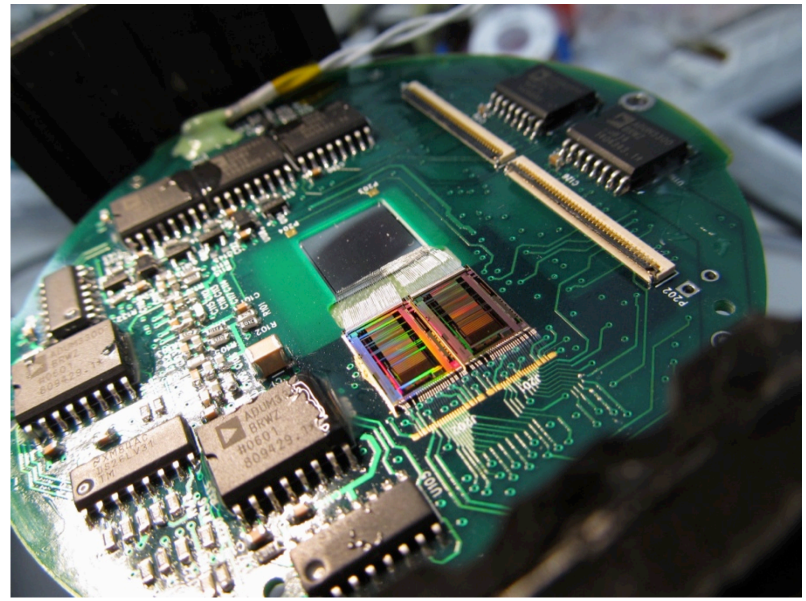
Readout ASICs: VATA451



Readout ASICs: VATA451

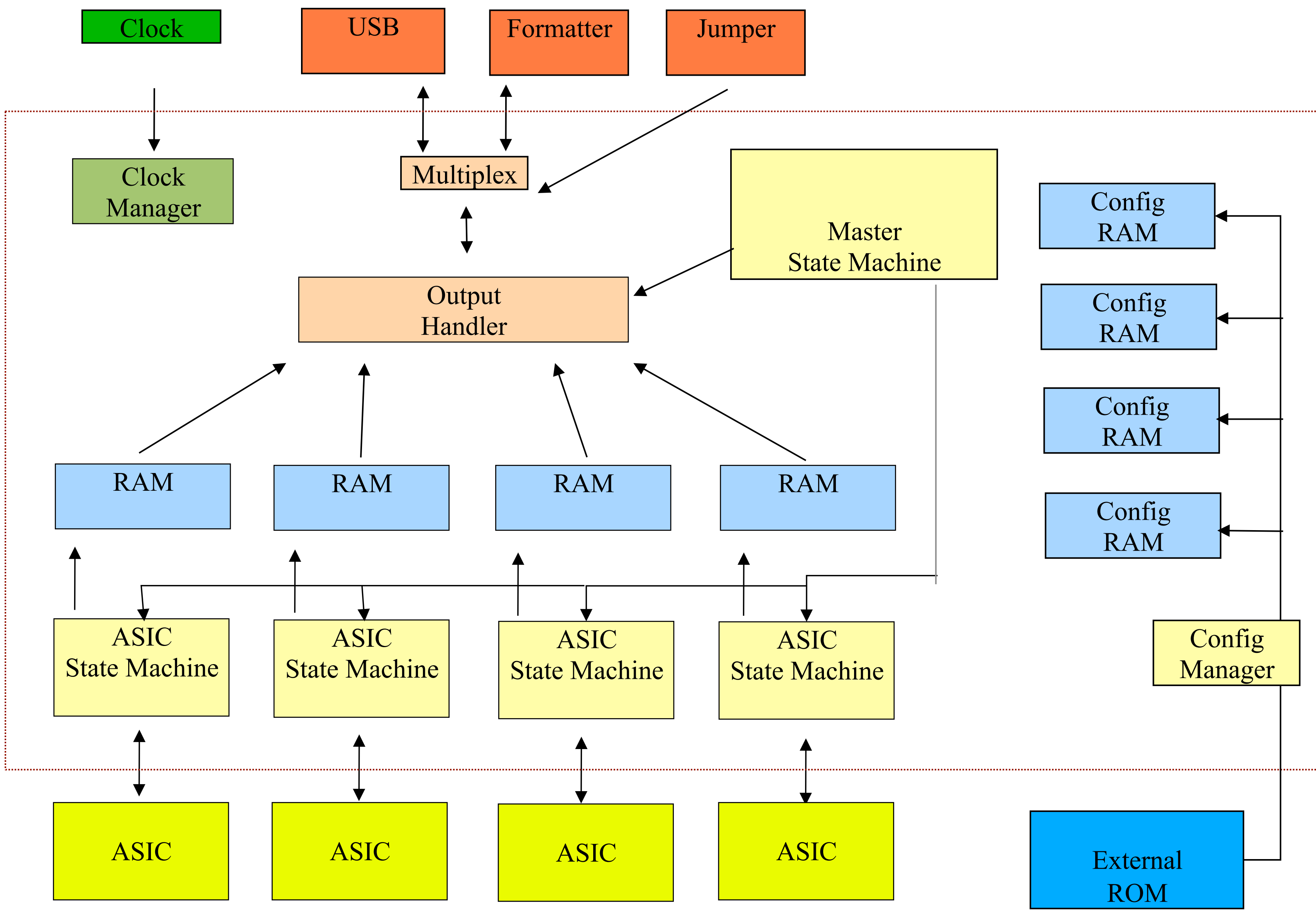
Threshold	0.2 fC (~4 keV γ)
Shaping time	3 us (slow shaper) 0.6 us (fast shaper)
Power	1 mW/ch
Channels	64

- Control register:
  - ADC ramp speed
  - Ramp offset
  - Threshold (global or per channel)
  - Channel disable
  - Gain each shaper
  - Low noise or low power



- Dummy channel
  - Not connected to external source
  - Used as baseline for ADC
  - Adjusts for changes due to temperature, etc.

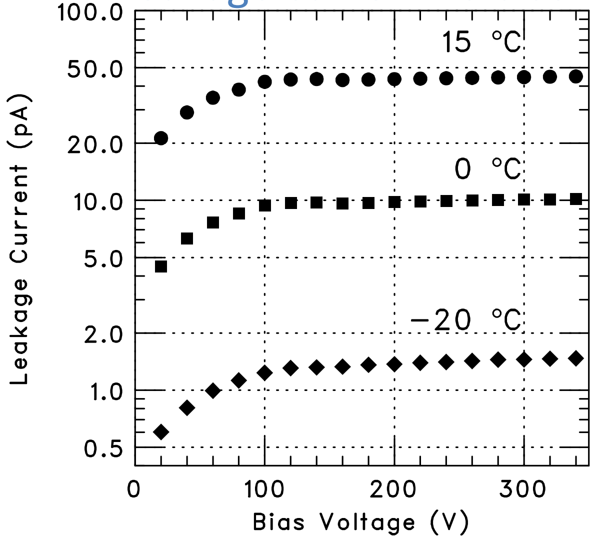
FPGA design


Clock
USB
Formatter
Jumper
Clock Manager
Multiplex
Master State Machine
Config RAM
Config RAM
Config RAM
Config RAM
Output Handler
RAM
RAM
RAM
RAM
ASIC State Machine
ASIC State Machine
ASIC State Machine
ASIC State Machine
Config Manager
ASIC
ASIC
ASIC
ASIC
External ROM

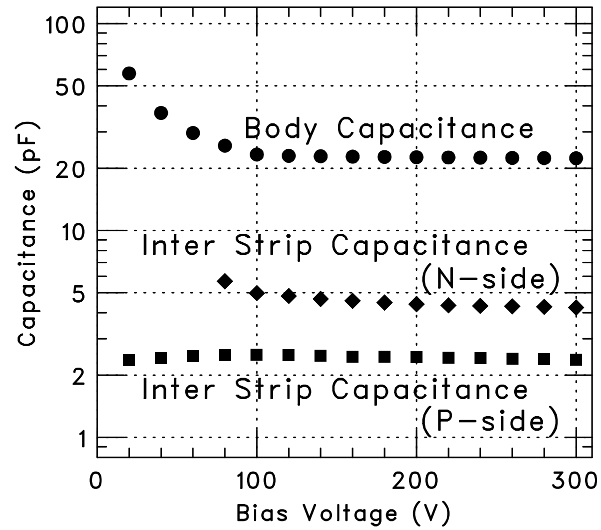
Detector tests

ISAS detector tests

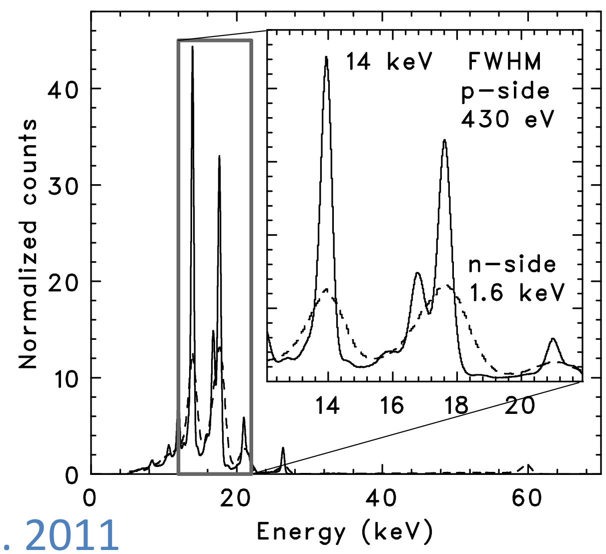
Leakage current vs bias V



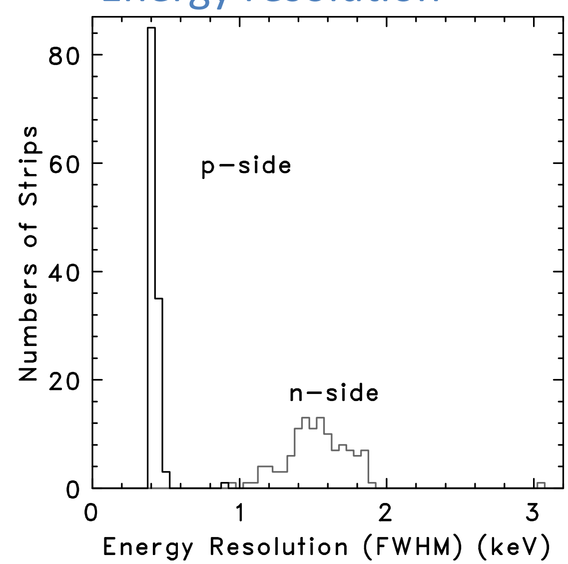
Capacitance vs bias



Am241 spectrum



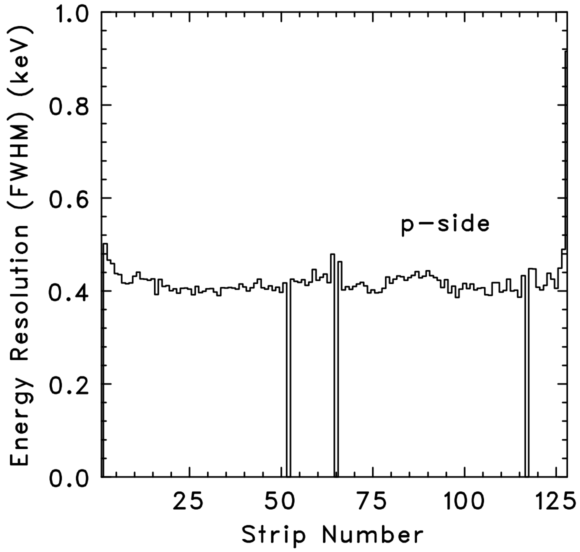
Energy resolution



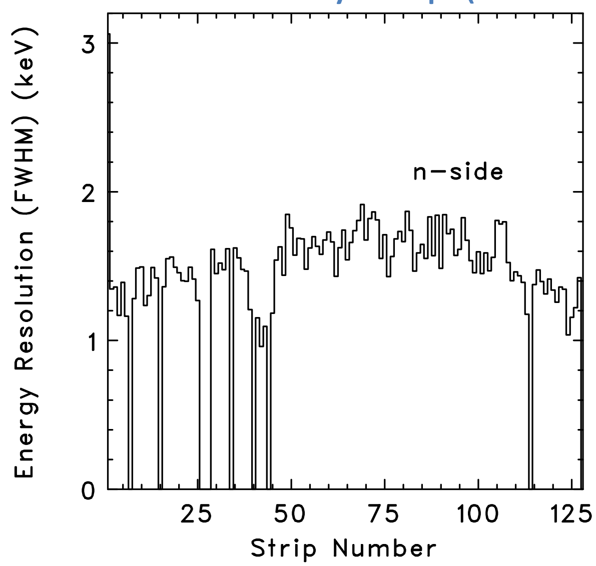
Ishikawa et al. 2011

ISAS detector tests

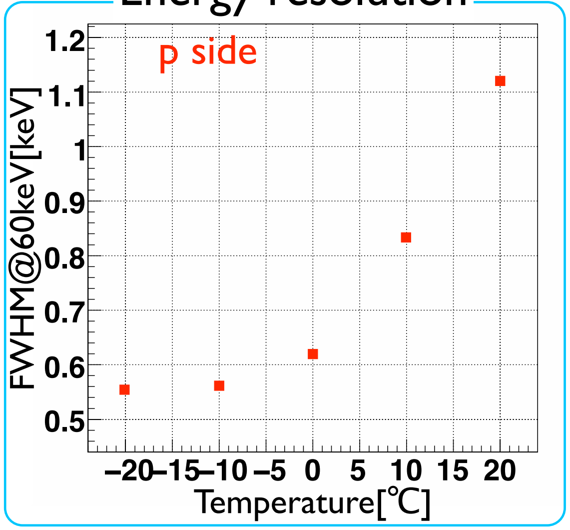
Resolution by strip (p-side)



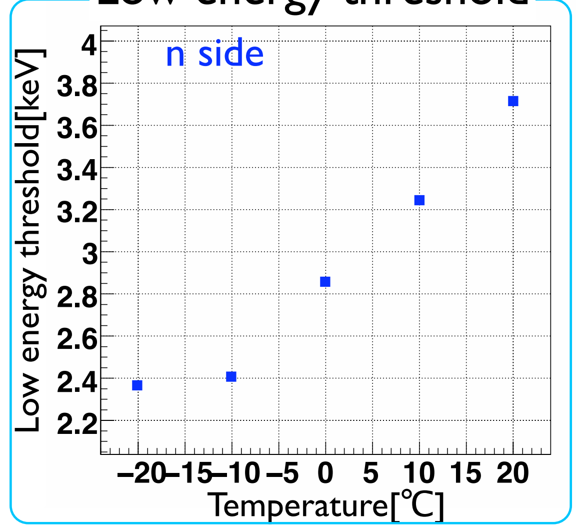
Resolution by strip (n-side)



Energy resolution



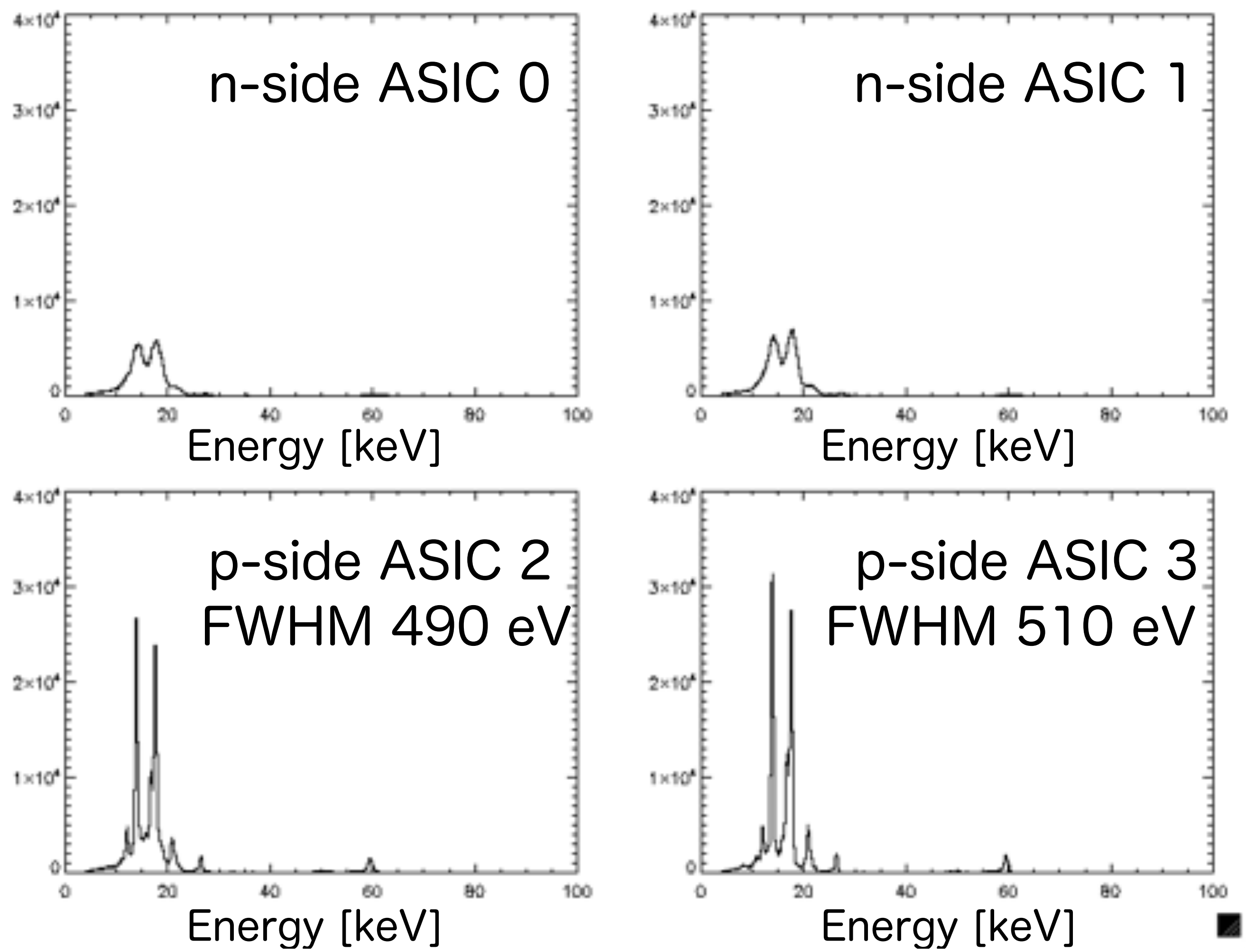
Low energy threshold



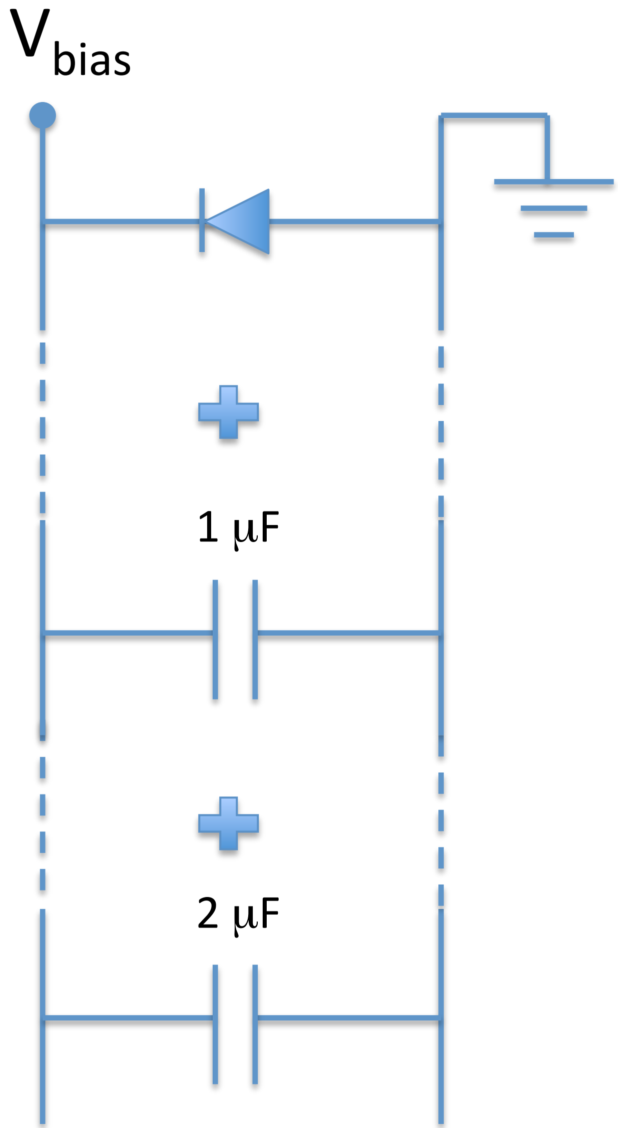
Ishikawa et al. 2011

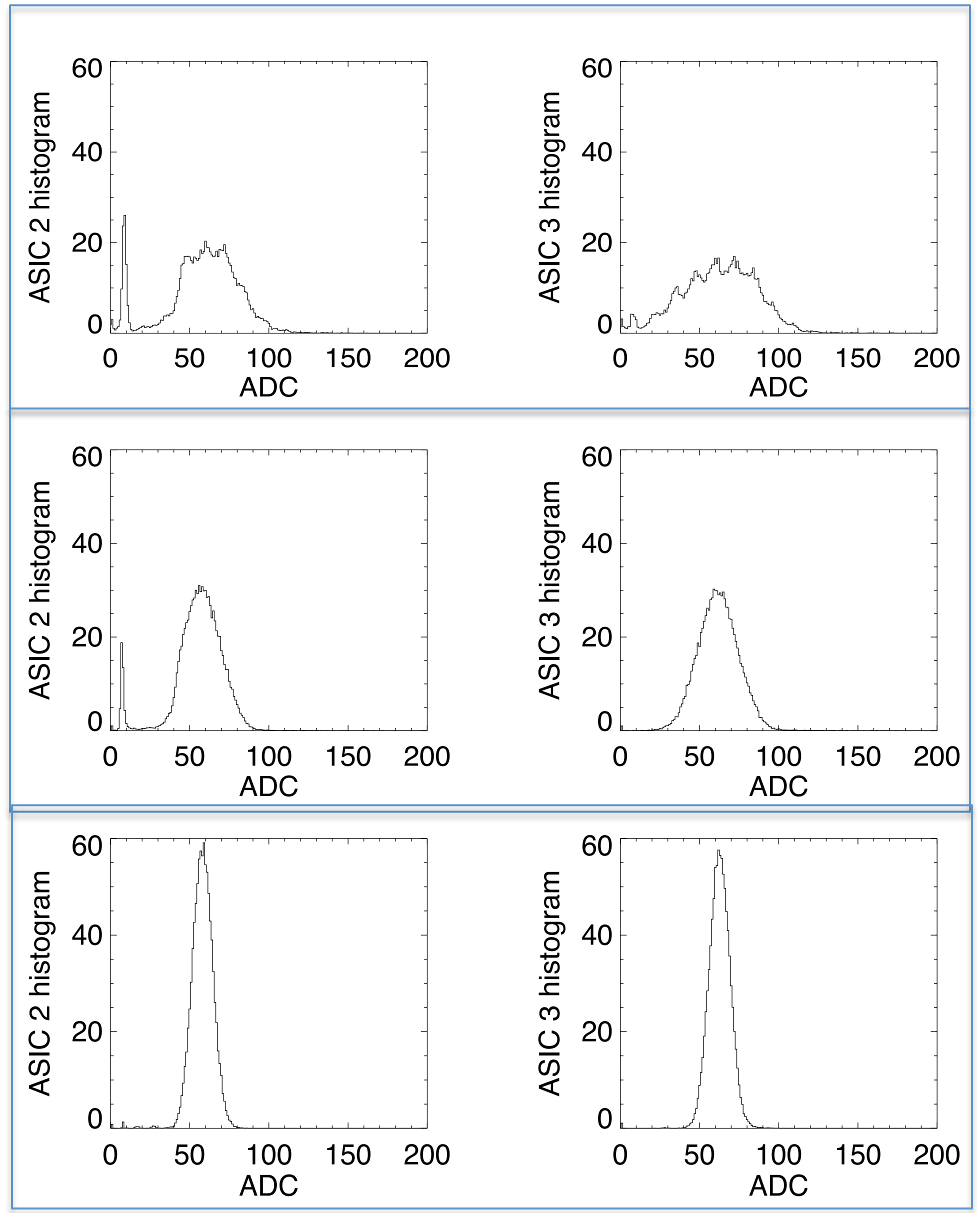
SSL detector tests

Am241 spectrum

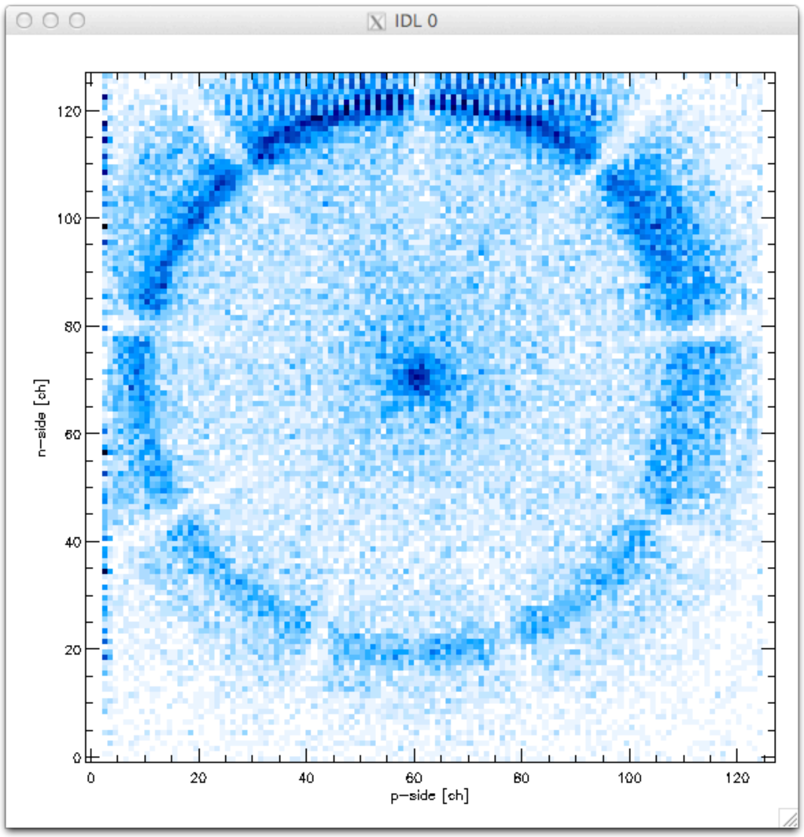


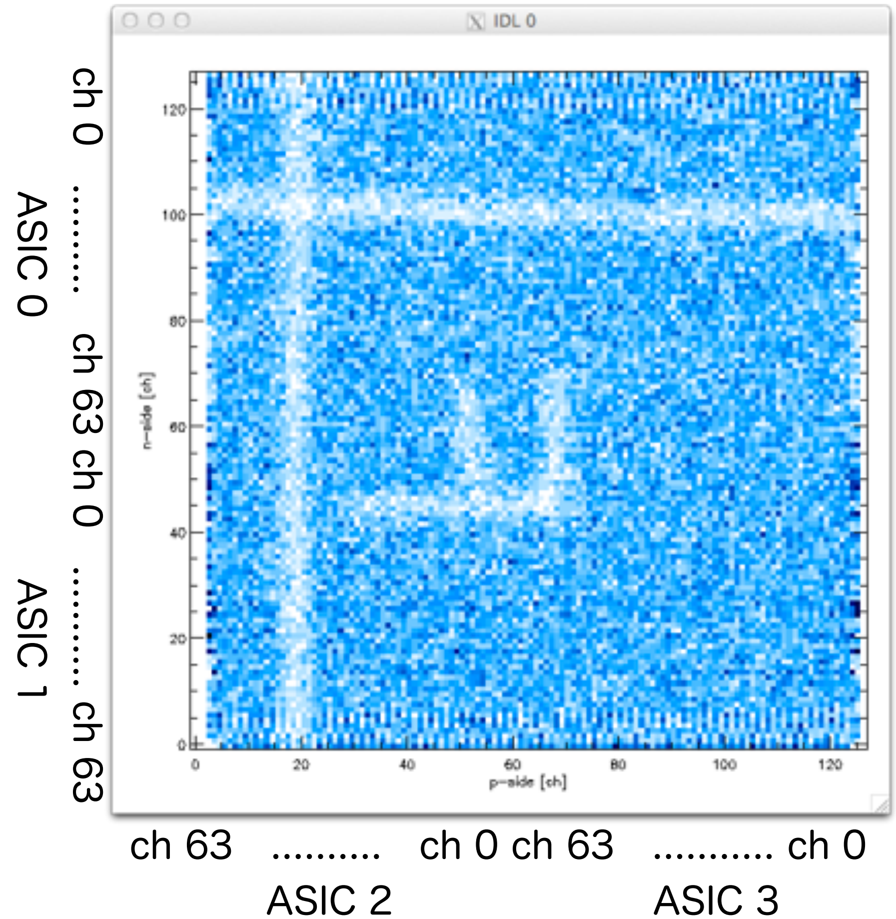
Pedestal noise



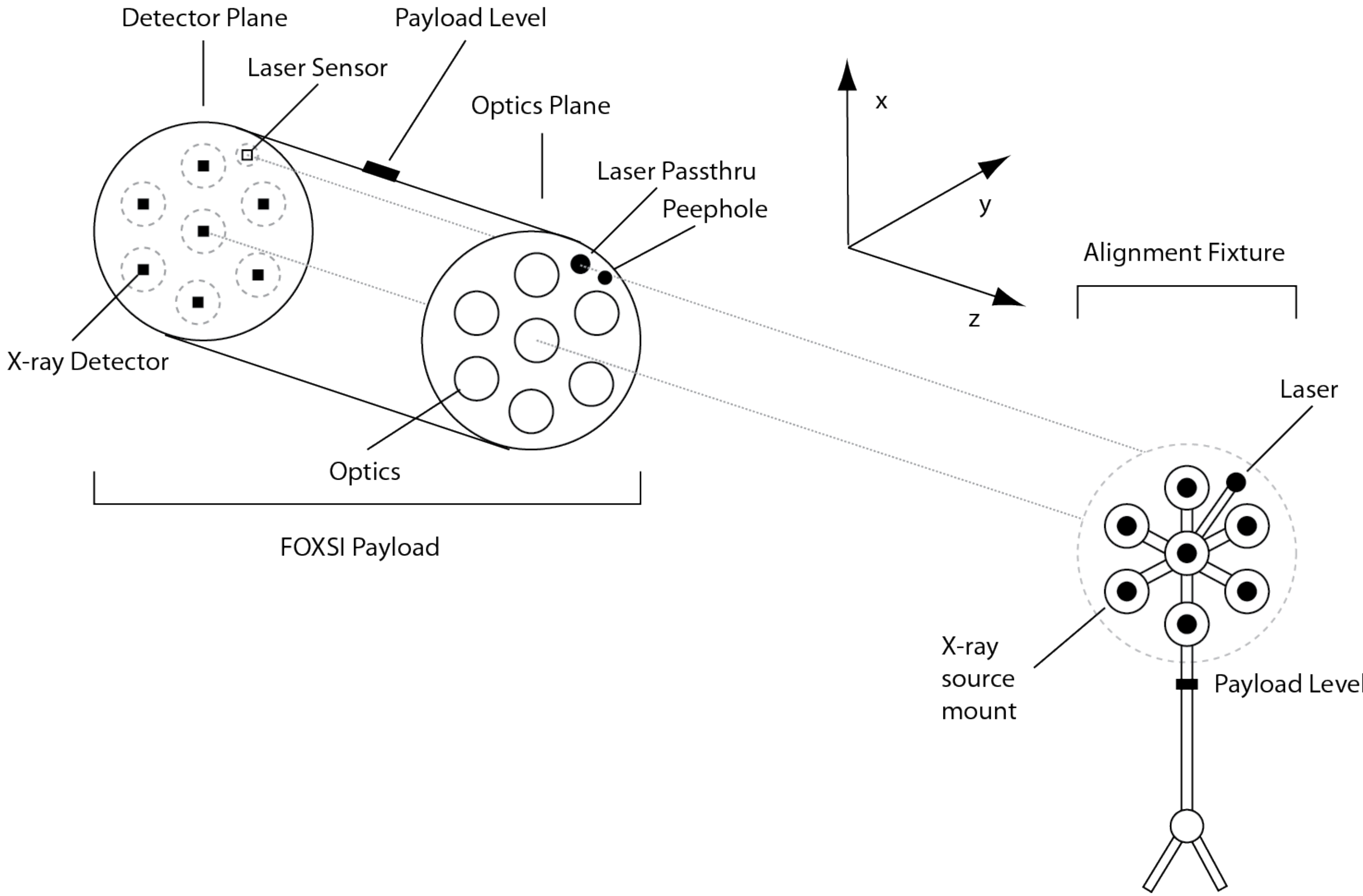


Imaging tests

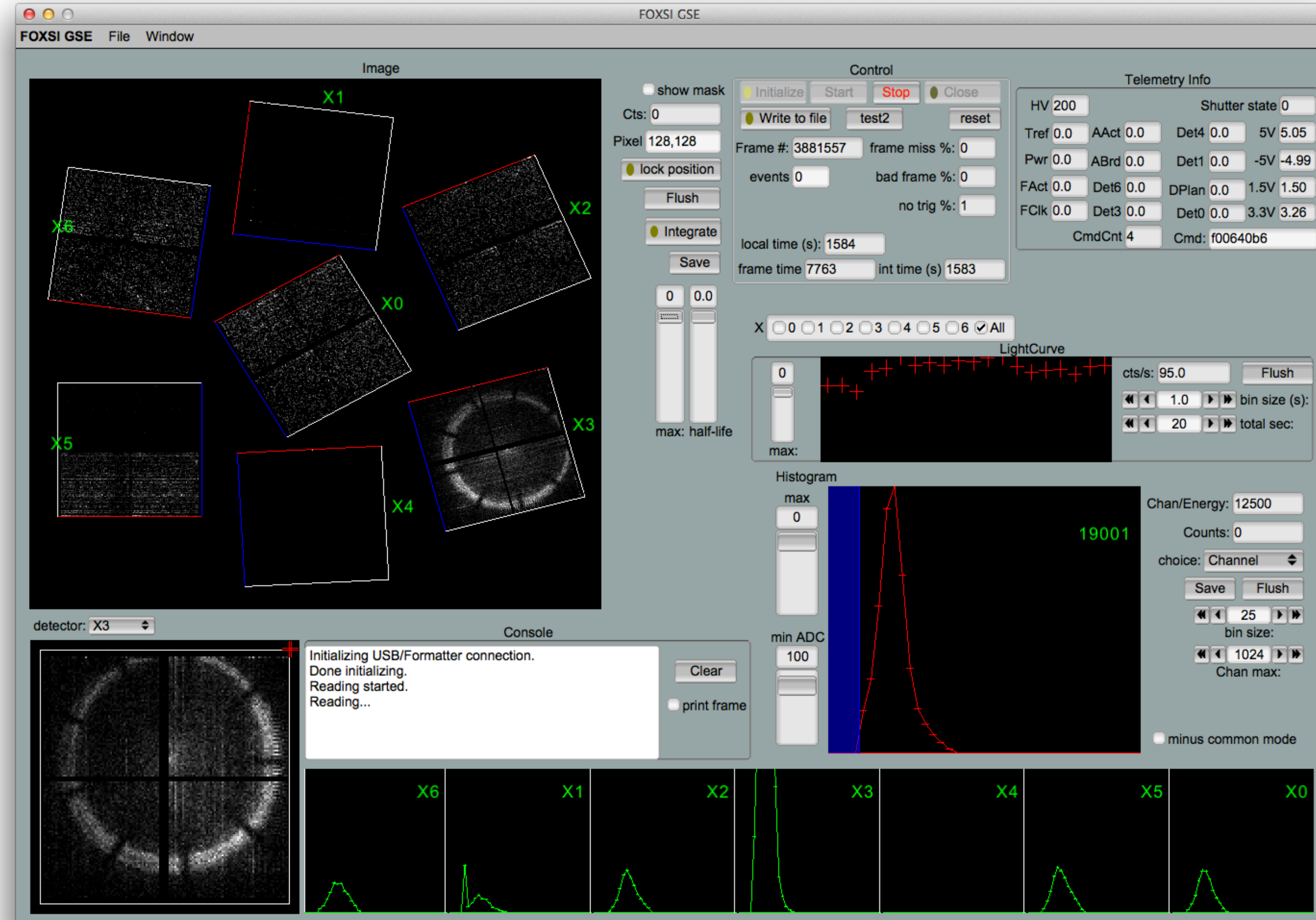




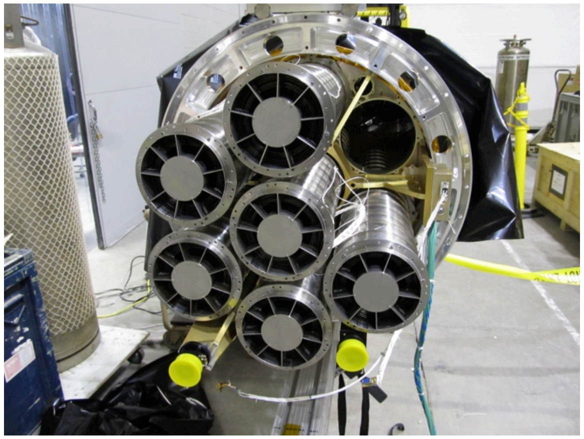
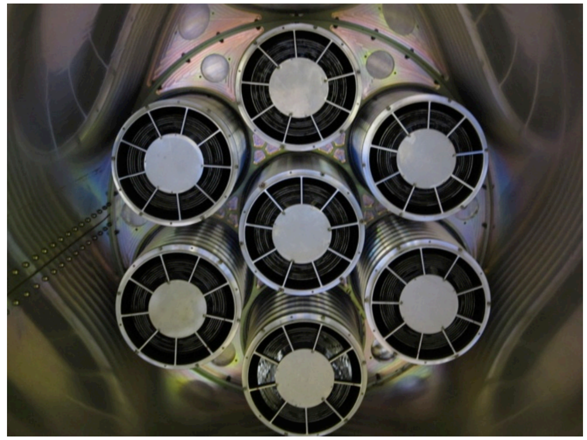
Optic/detector alignment

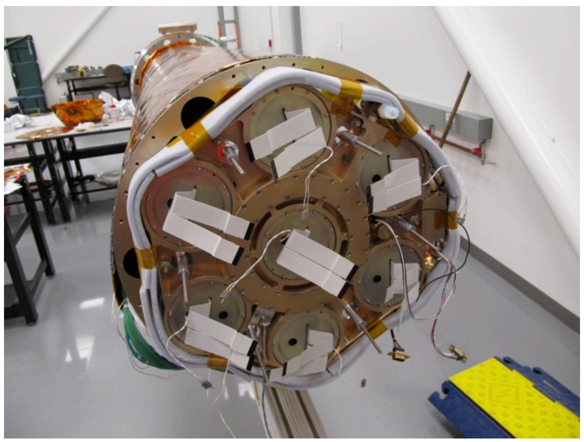
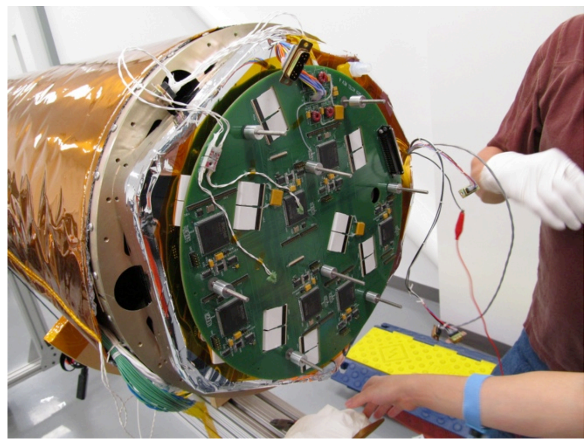
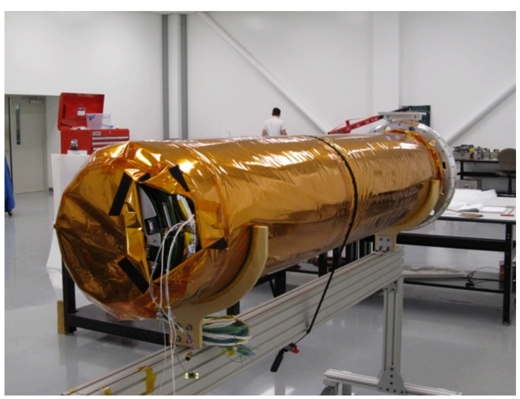


FOXSI ground station software



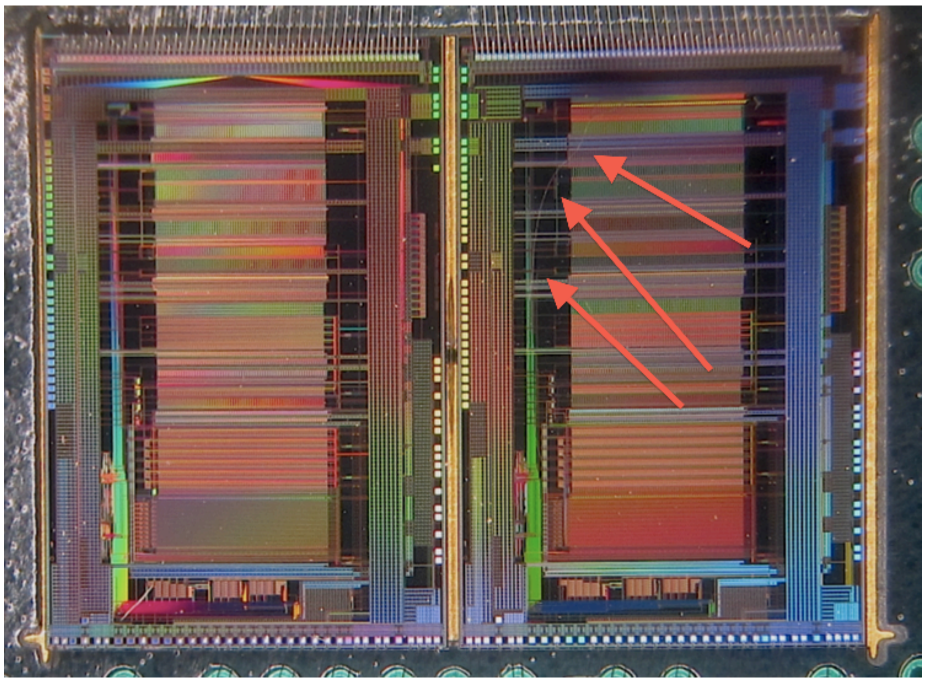
White Sands Missile Range

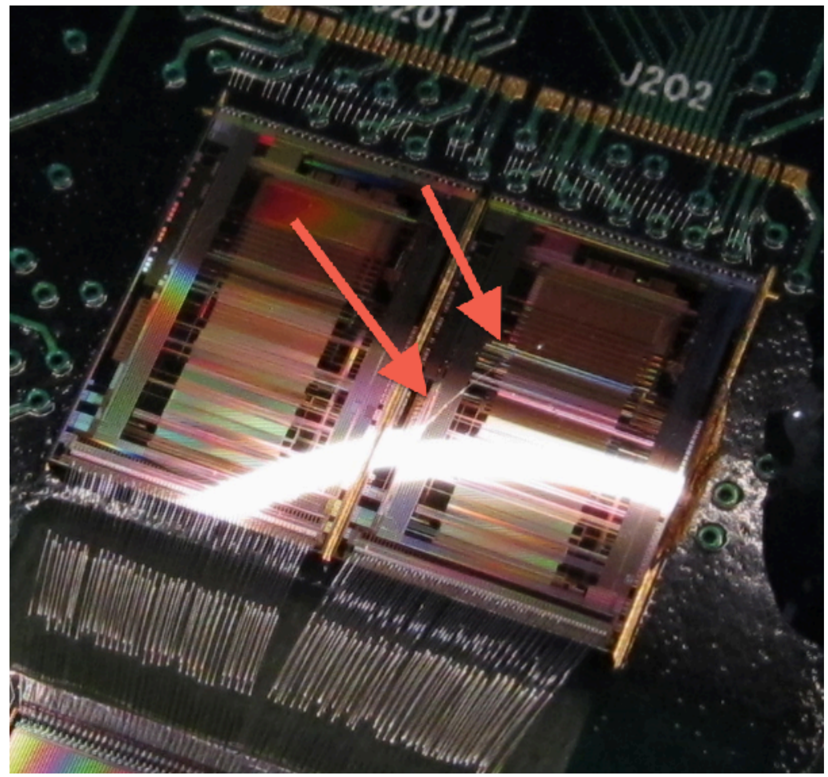




Cooling anomaly

- Sigma C4 controller + LN2 dewar cools detectors to -25 deg C.
- Operate cooler locally (controller box) or remotely (computer/RS232).
- Detaching a sensor *may* cause discrepancies between values/commands in local vs remote modes.
- In our case, control was accidentally switched to an unused sensor and the system was cooled to < -180 deg C.

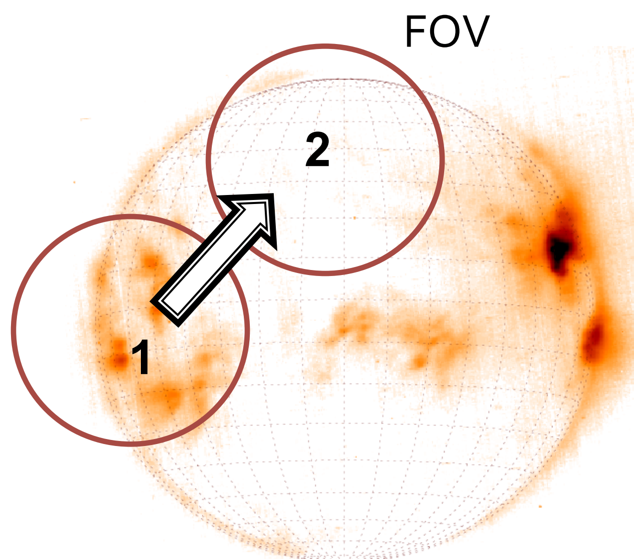




Plans (immediate future)

- Rebuild detector system, summer 2012

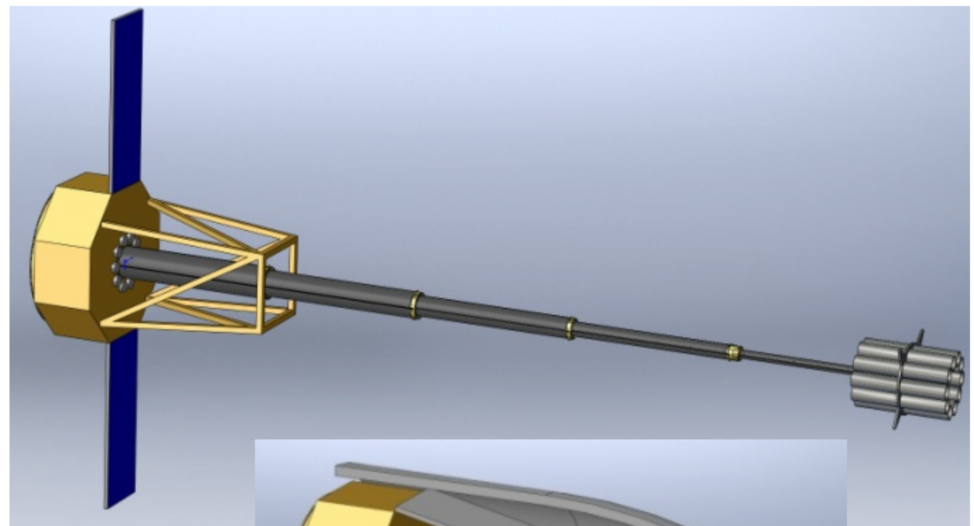
- Fall 2012: Rocket flight #1
  - 15 min, 5-6 min >150 km
- Targets:
  1) Low-activity active region
  2) Quiet Sun (nanoflares)

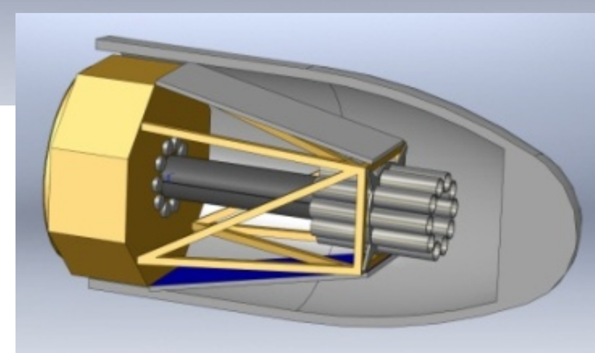


- Rocket flight #2 in 2014
  - Add inner shells to optics
  - Upgrade to CdTe detectors

Plans, later…

- Propose a spaceborne FOXSI based on this technology.
  - Improved sensitivity
    - More shells
    - More modules
  - Higher energy coverage
    - Increased focal length
    - CdTe or CdZTe detectors
- Possible observations:
  - Flare acceleration regions
  - Quiet Sun nanoflares
  - Active Region microflares
  - Type III radio-emitting beams

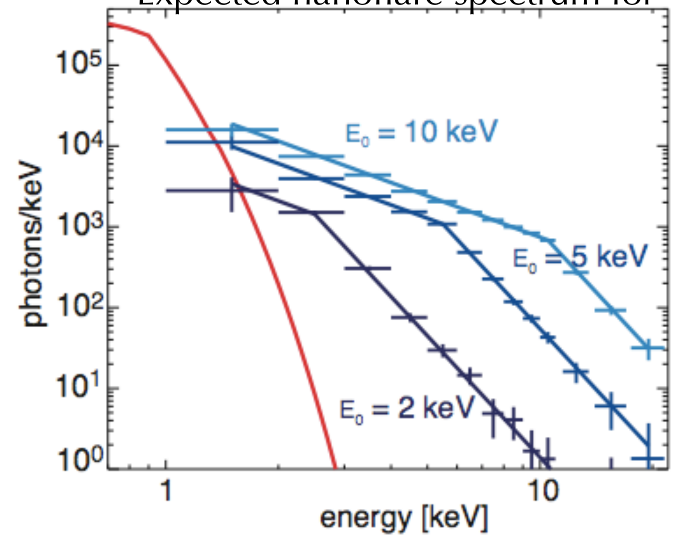




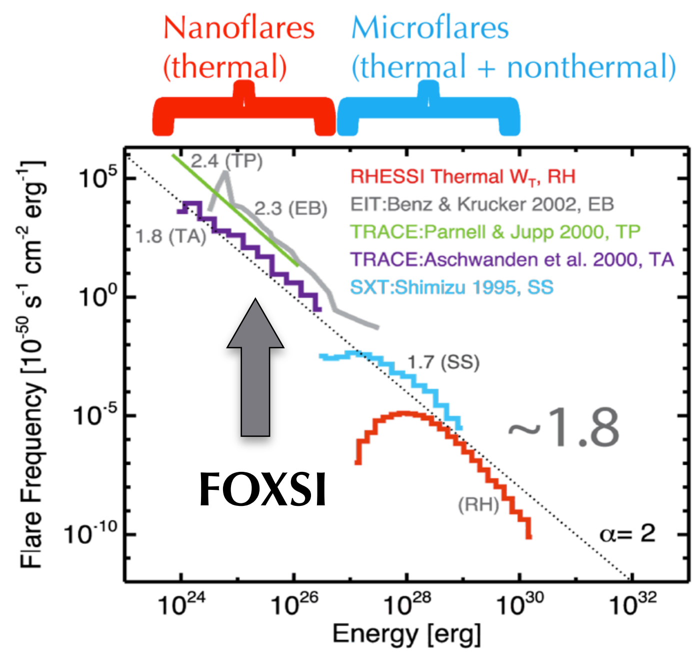
FOXSI science

- FOXSI will measure the nonthermal components of nanoflares.
- Photon spectrum
  --> invert assuming thick target
  --> energy in nonthermal e$^-$
- Nanoflares have already been detected at lower energies (extreme ultraviolet, thermal)
- Hannah et al. (2008, ApJ 724) have attempted to measure this component using RHESSI, but only upper limits have been set.

Expected nanoflare spectrum for

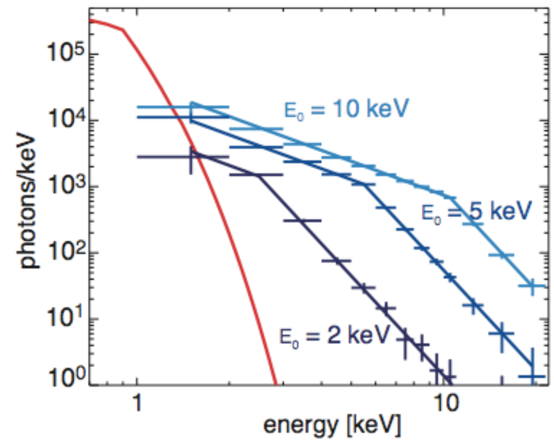


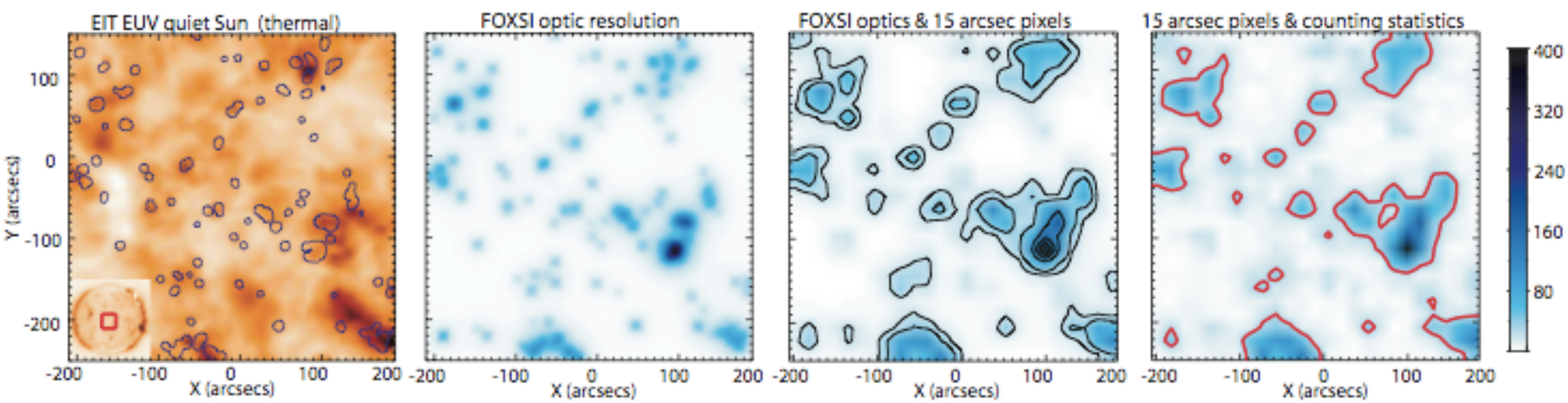
T~2 MK
EM~10^{44}
E~5x10^{25} ergs
Dt = 60 s



HXR from the Quiet Sun

- Heating events are observed in the "quiet" Sun network (Krucker & Benz 1998, Parnell & Jupp 2000, Aschwanden 2000).
- Expected parameters:
  T~2MK, EM~10^{44} cm, E~5×10^{25} ergs, Dt = 60s
- Expected FOXSI observations
- Photon spectrum --> invert using thick target approximation --> energy in nonthermal electrons.



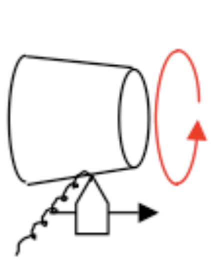



EXIT

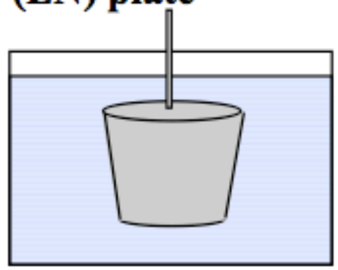
Extras

FOXSI Optics Fabrication

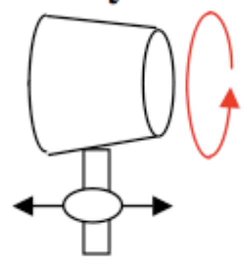
1. CNC Machine, Mandrel Formation From Al Bar



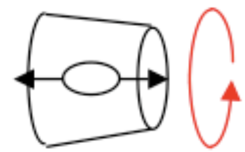
2. Chemical clean and activation & Electroless Nickel (EN) plate



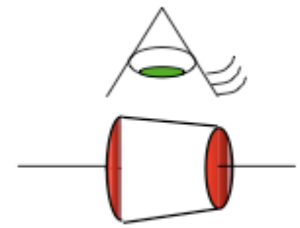
3. Precision Grind to 600Å, sub-micron figure accuracy



4. Polish and Superpolish to 3 - 4Å rms finish

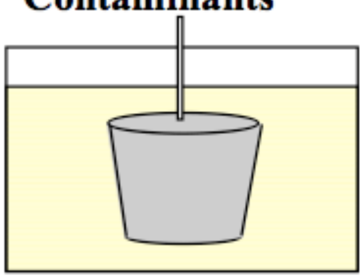


5. Metrology On Mandrel

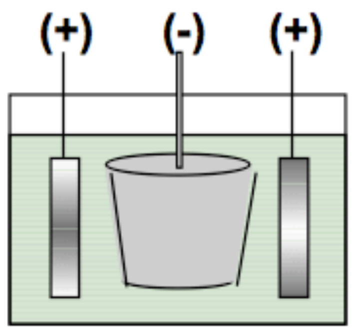


Shell Fabrication

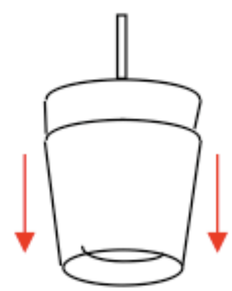
6. Ultrasonic clean and Passivation to Remove Surface Contaminants



7. Electroform Ni Shell onto Mandrel

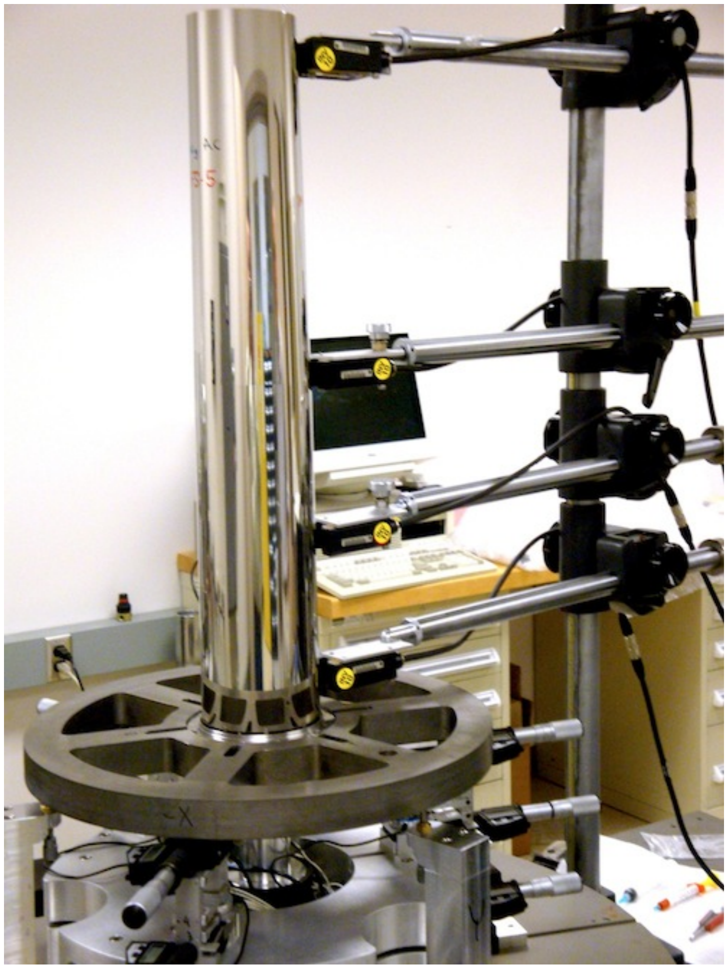


8. Separate Optic From Mandrel in Cold Water Bath



Process by B. Ramsey at the M.S.F.C.

Shell Alignment Process

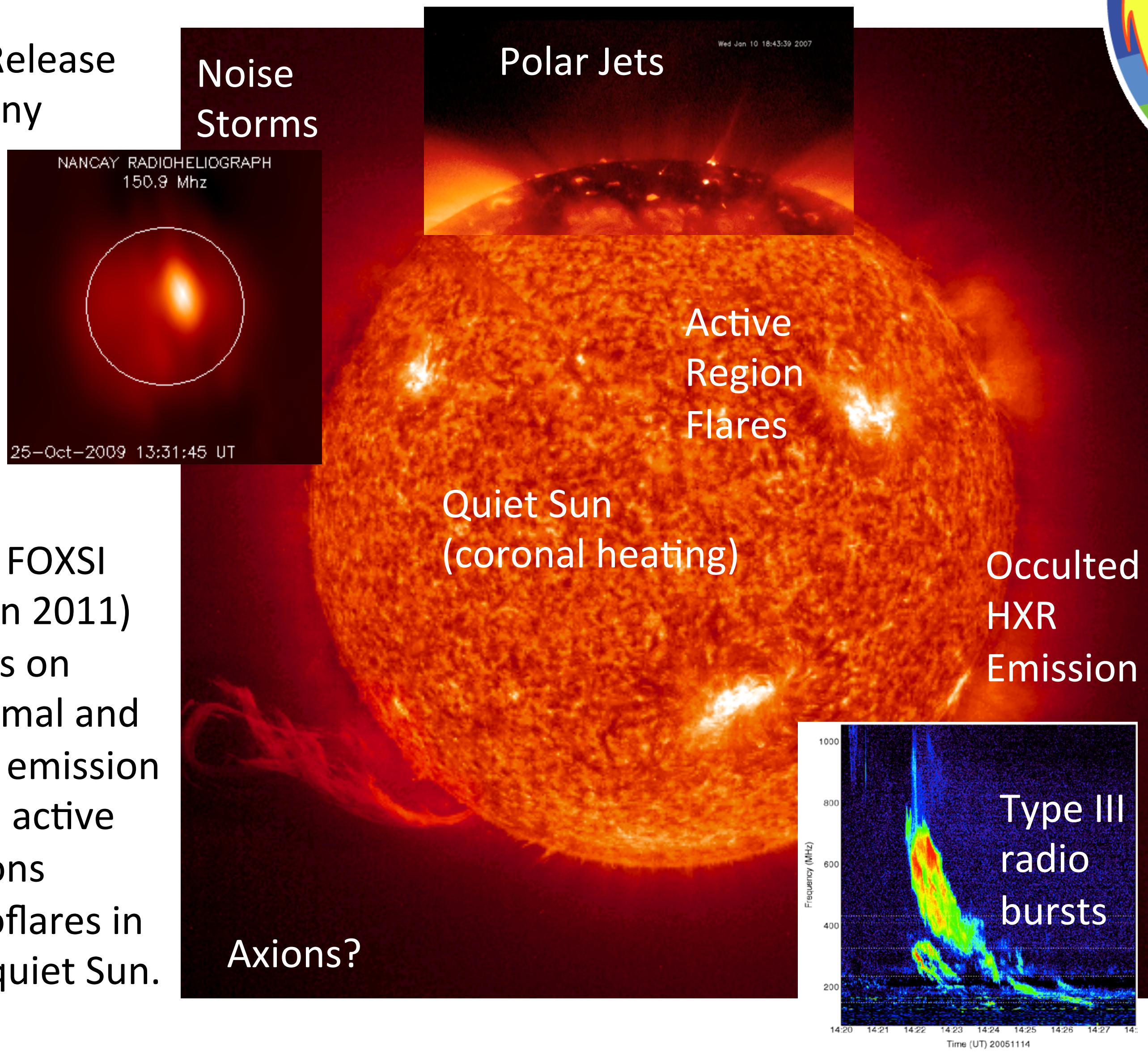


Module Integration stand

- Shells are built up from the inner to outer.
- Micropositioners at three points are used to enforce circularity before bonding.
- The circularity of each shell is monitored in real time during bonding process.

FOXSI Science Targets

Energy Release in its many forms…



The first FOXSI flight (Jan 2011) will focus on

1. thermal and flare emission from active regions
2. nanoflares in the quiet Sun.

Many science targets are available for future FOXSI flights!