The Focusing Optics X-ray Solar Imager Small Explorer Concept Mission (FOXSI)

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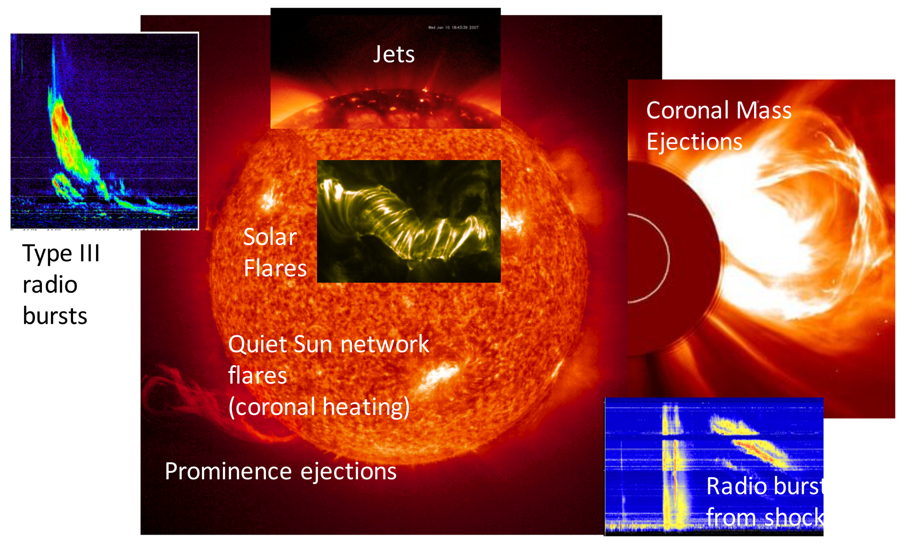
Abstract
We present the FOXSI (Focusing Optics X-ray Solar Imager) small explorer (SMEX) concept, a mission dedicated to studying particle acceleration and energy release on the Sun. FOXSI is designed as a 3-axis stabilized spacecraft in low-Earth orbit making use of state-of-the-art grazing incidence focusing optics combined with pixelated solid-state detectors, allowing for direct imaging of solar X-rays. The current design being studied features multiple telescopes with a 14 meter focal length enabled by a deployable boom. FOXSI will observe the Sun in the 3-80 keV energy range. The FOXSI imaging concept has already been tested on two sounding rocket flights, in 2012 and 2014 and on the HEROES balloon payload flight in 2013. FOXSI will image the Sun with an angular resolution of 8'', a spectral resolution of 0.8 keV, and sub-second temporal resolution. FOXSI is a direct imaging spectrometer with high dynamic range and sensitivity and will provide a brand-new perspective on energy release on the Sun. We describe the mission and its science objectives.

Science

The goal of the FOXSI mission is to investigate impulsive energy release on the Sun by searching for hard x-ray signatures of hot and accelerated electrons in the solar corona where there are accelerated and heated.



Energy release on the Sun comes in many forms such as solar flares, solar eruptions such as jets, coronal mass ejections and prominence ejections. Smaller more fundamental energy release processes likely permeate active regions and the quiet Sun in the form of so-called nanoflares. These may be major contributors to coronal heating.

Science Traceability Matrix

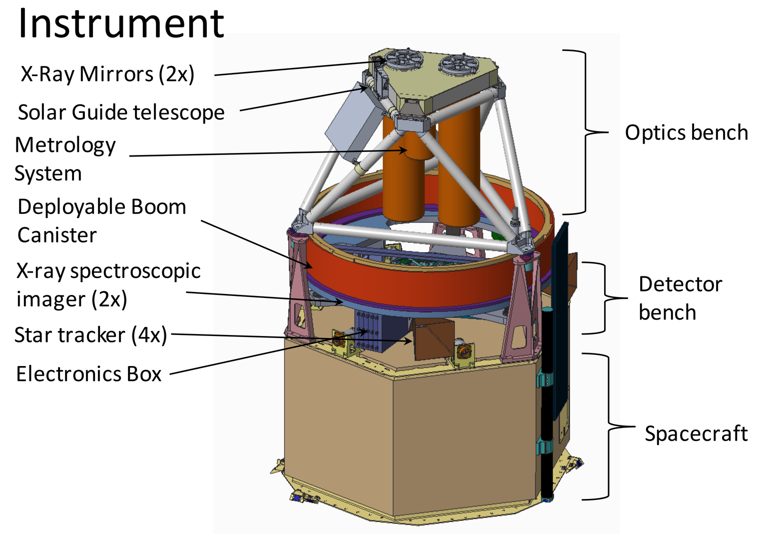
The scientific questions and objectives that FOXSI will address are listed below in its scientific traceability matrix. These objectives are related to physical parameters and associated observable.

Science Question	Science Objective	Physical Parameter	Observable Parameter
1. How are particles accelerated at the Sun?	1.1 Where are electrons accelerated and on what time scales?	Flare-Accelerated electron energy spectrum as a function of time and space in the corona	Nonthermal HXR spectra as a function of time and space in the corona
	1.2 What fraction of electrons are accelerated out of the ambient medium?		
	1.3 Where do escaping flare-accelerated electrons originate?		
2. How do solar plasmas get heated to high temperatures?	2.1 What is the energy input of accelerated electrons into the chromosphere and corona?	Accelerated electron energy spectrum as a function of time and space in the chromosphere and corona	Nonthermal HXR signatures as a function of time and space in the chromosphere and corona
	2.2 How do super-heated coronal plasmas originate and evolve?	Temperature distribution of hot coronal plasma and the accelerated electron energy distribution	X-ray thermal and nonthermal spectra in flares
	2.3 How much do flare-like processes heat the quiescent corona?	Temperature distribution of hot coronal plasma above 5 MK	X-ray thermal spectra from the quiet Sun and active regions
3. How does magnetic energy release on the Sun lead to flares and eruptions?	3.1 How does coronal energy release and the resulting accelerated particles drive the evolution of flares and associated magnetic structures?	Motion and location of coronal and chromospheric sources	X-ray source positions as a function of time
	3.2 How do energy release processes scale from the smallest bursts to the largest flares?	Flare properties (e.g. morphology, thermal energy, nonthermal energy) for a broad range of sizes.	X-ray thermal and nonthermal spectroscopic imaging for a broad range of flare X-ray fluxes

Overview of Instrument

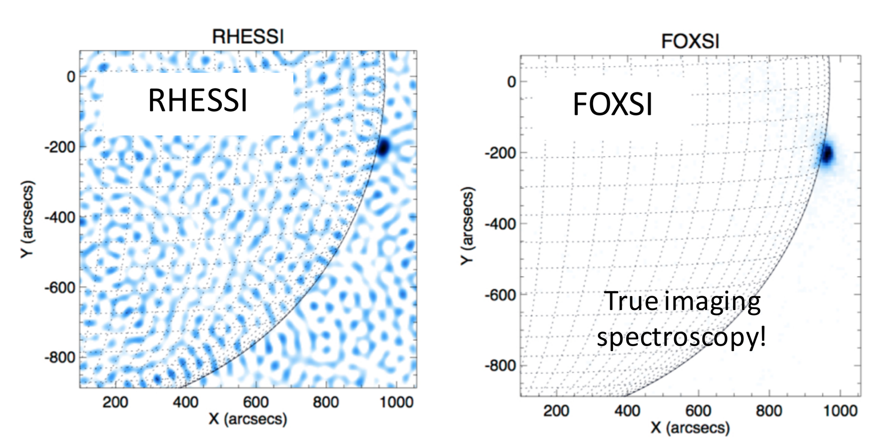
FOXSI will provide new and important new observations by combining, for the first time, hard x-ray focusing optics and pixelated detectors on a solar-dedicated satellite.

Instrument



Stowed/launch configuration

FOXSI will make use an extendable boom to support the 14 m focal length of the hard x-ray focusing optics. The optics will be held on an optical bench along with a guide telescope and a metrology system. The guide telescope will provide precise measurements of where the optics are pointed while the metrology system will measure where the detectors are with respect to the optical optics. FOXSI will have two identical telescope modules to provide increased collecting area, redundancy, as well as the capability to measure both thermal and nonthermal emission at the same time.



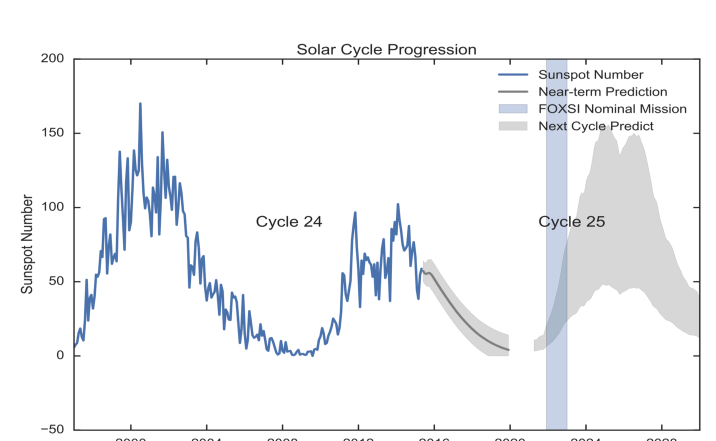
Expected Performance
Angular Resolution: 8" FWHM over 300"
X-ray energy Resolution: • 0.8 keV FWHM
Time Resolution for imaging spectroscopy: 0.1 sec
Effective Area: 55 cm^2 up to 50 keV
Dynamic range (imaging): • 20:1 at 20" • 1000:1 at 45"
Flux range: <A to X20 flares
Low Energy Threshold: 3 keV
Field of View: 9 x 9 arcmin

The expected performance of the instrument is described above. FOXSI will be able to provide true spectroscopic imaging with a time resolution of 0.1 s with an angular resolution of better than 8 arcsec.

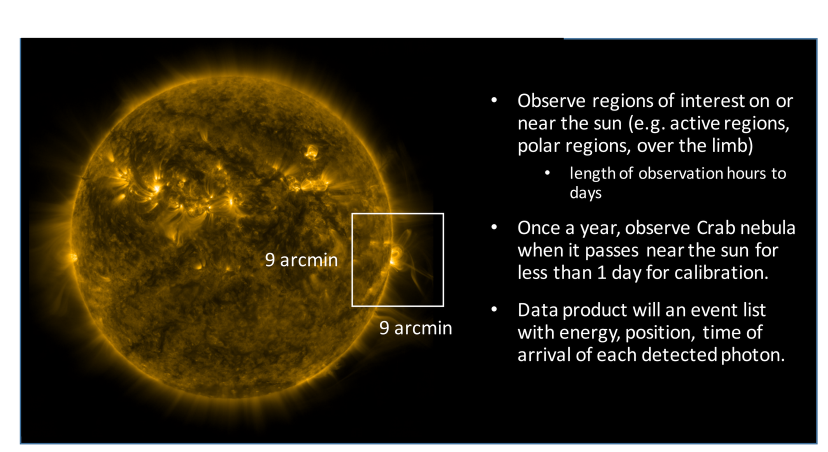
Mission Concept

Parameter	Value
Launch Date	12/1/2021
Orbit	LEO, 600 km, 6 degree (low radiation environment)
Mission	SMEX 2 years
Spacecraft	3-axis stabilized (reaction wheels, torque bars)
Telescope	Grazing-incidence ENR optics
Detectors	Spectroscopic Imager (HEXITEC)
Command/Tlm	S-band

The parameters of the mission concept include a low inclination orbit which will provide high quality (low background) observations of the Sun. The orbit will allow for solar observing for 60% of the time limited by eclipses.



The anticipated launch date of FOXSI is 12/2021 which is near the start of the next solar cycle provides good observations of both quiet Sun periods and more active times. This launch date is consistent with the requirements of the AO.



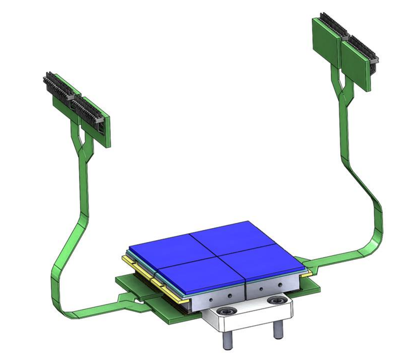
Since the field of view of FOXSI is 9 x 9 arcmin, weekly planning meetings will take place to decide on the target for the week. Reacting to targets of opportunity within less than a day will also be possible. Repointing to a new target will only take a few minutes. It is expected that this observing scenario will be similar to IRIS or TRACE.

Key Technologies

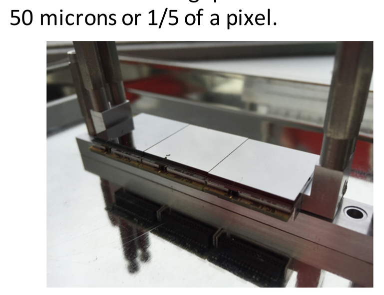
Detectors

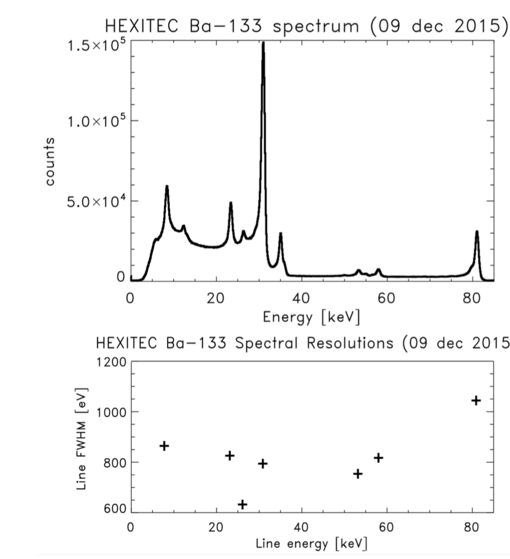
The baseline detector for FOXSI is based on the HEXITEC ASIC. Developed by the Rutherford Appleton laboratory, it provides the smallest independent pixels currently available and fast counting rates both important to solar observations.

Parameter	Value
Number of pixels	160 x 160
Energy Resolution	800 eV to 60 keV
Low energy threshold	3 keV
Pixel size	250 microns (3.7 arcsec)
Detector material	Cadmium Telluride
Size	4 cm x 4 cm
Intra-detector gap	~ 1/5 pixel
Pixel Counting Rate Capability	10,000 counts/s/pixel
Overall Counting Rate Capability	>100,000 counts/s/detector



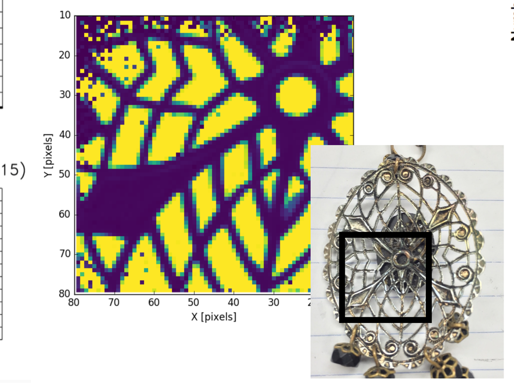
(Above) A diagram of a detector module which consists of a 2x2 detector array. (Below) A photograph of an existing and tested 3x1 system which recently passed a vibration test. The gap between detector is 50 microns or 1/5 of a pixel.

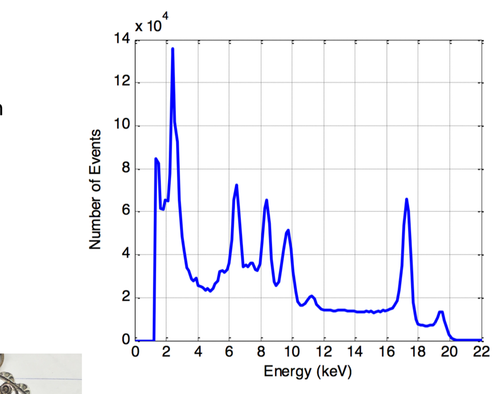




(Above) **Energy resolution better than 1 keV.** A spectrum of a Ba-133 source, co-added from all the pixels in the array after gain correction. The spectral resolution as a function of energy derived from the Ba-133 spectrum is shown in the bottom panel.

(Below): **Imaging at 250 microns.** An x-ray image of an earing taken with HEXITEC. A photo is shown for comparison.





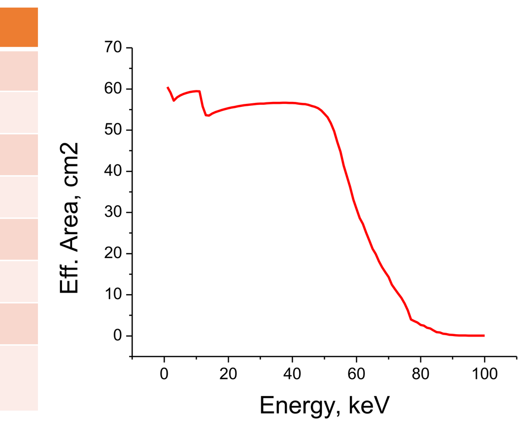
(Above) **Low energy threshold below 4 keV.** A HEXITEC low-energy spectrum of molybdenum fluorescence lines from a 10x10 pixel array. The Mo-L peak at 2.3 keV is clearly distinguishable above the threshold.

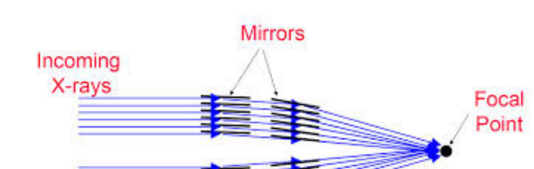
For more information see poster **P8.11**

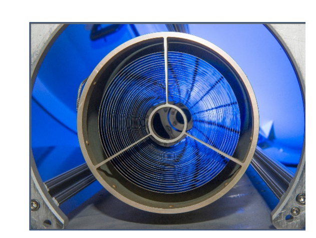
Hard X-ray Optics

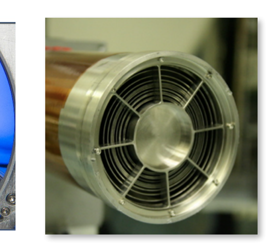
FOXSI will make use of hard x-ray focusing optics to provide the highest angular resolution focused hard x-ray images of the Sun currently available with large collecting area. These optics image x-rays by reflecting x-rays at very shallow . Typical mirror configuration uses a combination of parabola and hyperbola to reduce aberrations. Many such mirrors are then concentrically nested to increase effective area. A diagram of how these mirrors work is shown below along with two photographs of existing telescopes modules (left, ART-XC, right FOXSI sounding rocket).

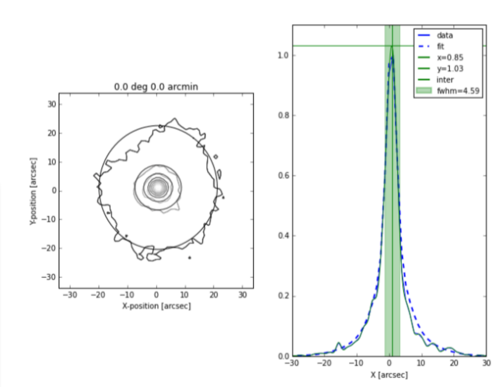
Parameter	Value
Number of modules	2 + 1 spare
Focal length	14 meters
Number of shells	20
Angular Resolution	< 7 arcsec (FWHM)
Shell material	Nickel-cobalt alloy
Outer shell diameter	176 mm
Inner shell diameter	108 mm
Effective area	55 cm^2 (at 8 keV)





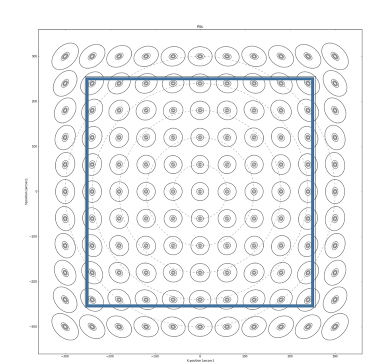






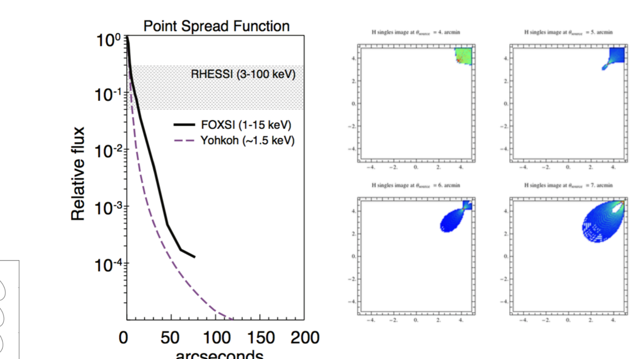
(Left) **PSF at the center of the optical axis.** The point spread function compared to measured data shows a FWHM of <5 arcsec.

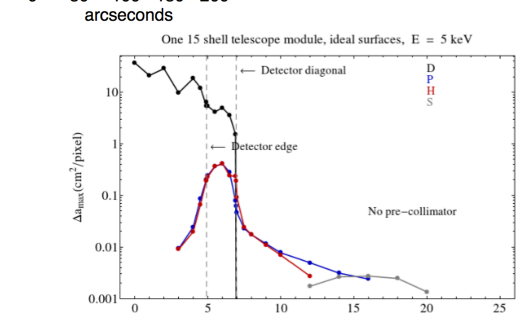
(Right) **PSF across the field of view.** The shape of the PSF as a function of its position across the FOXSI field of view (blue box).



Imaging Dynamic Range

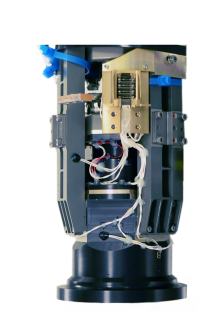
The imaging dynamic range for nearby sources is set by the shape of the mirrors. For well separated sources (>45 arcsec) scattering becomes a larger contributer. The figure below shows the PSF provides 1000:1 imaging dynamic range for well separated sources. Sources even further away can limit the dynamic range through so-called single bounce photons. The FOXSI optics design is optimized to reduce this contribution as much as possible. Sources outside the field are attenuated by a factor of > 500 compared to those in the field of view.





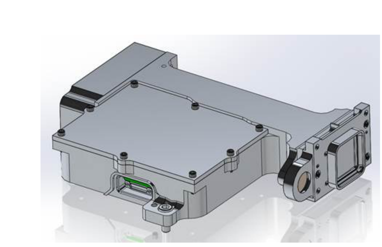
Support Sub-systems

Aspect Knowledge system

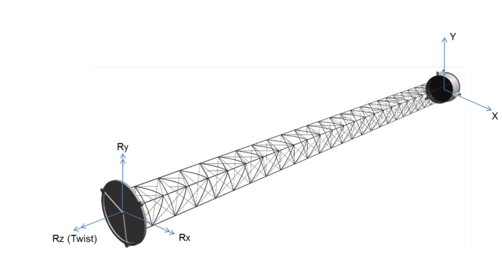


FOXSI is a photon counting experiment combined with the fact that the boom is not perfectly stiff means that the system requires a system that can determine the origin of each photon. This is provided by the aspect knowledge system which consists of the solar guide telescope and the metrology system.

Metrology System
- Consists of a camera on the optics bench which images LEDs on the detector bench.
- Based on IceSat LRS system.
- Provide relative alignment accuracy better than 1 arcsecond on all three axes
- Data acquisition rate >= 20 Hz



Solar Guide Telescope
- Built by LASP
- Provides linear field-of-view >= 3° total
- Provide knowledge accuracy better than 1 arcsec with stability better than 1 arcsec
- Data acquisition rate >= 20 Hz

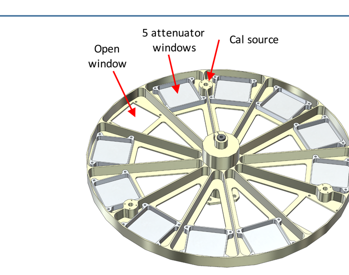


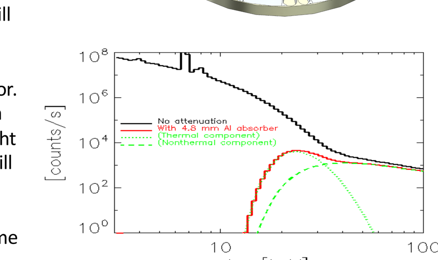
Boom

- Built by ATK/Goleta
- Three-sided, coilable/deployable boom
- 13.5 meters long
- Carbon fiber, low mass <5 kg
- High heritage and 100% successful deployment

Filter Wheel

In order to observe both the largest flares as well as the quiet Sun, FOXSI will make use of a filter wheel with a variety of attenuators which preferentially block out the low energy photons to stop the detectors from saturating. This wheel will be able to support up to 5 different attenuator combinations for each detector. An example of the effect of an attenuator is shown to the right on an X4.8 flare. This wheel will also hold up to 3 radiation sources to provide gain measurements over the lifetime of the mission.

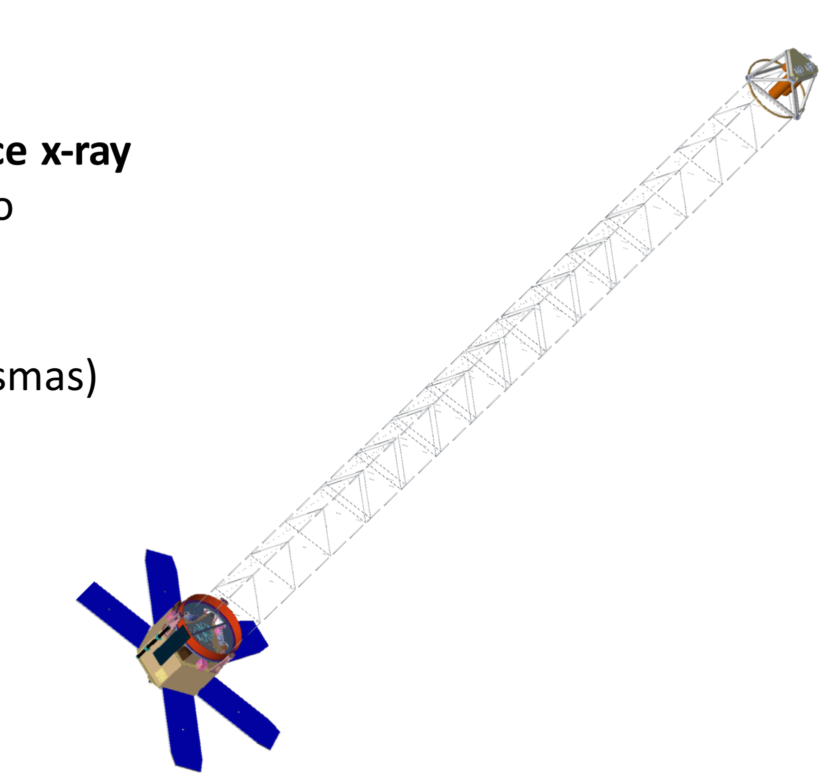




Conclusion

FOXSI will combine, for the first time, high angular resolution **grazing-incidence x-ray focusing optics** with fast and high resolution **solid-state pixelated detectors** to observe the Sun.

- FOXSI will investigate compelling new science by focusing on
  - Fundamental physics (acceleration processes in magnetized plasmas)
  - Link between the Sun and the Earth (space weather)
- FOXSI will provide new observations of the Sun in hard X-rays with
  - **>10 times better sensitivity and dynamic range** than previous instruments (e.g. RHESSI).
  - **True hard x-ray imaging spectroscopy with >10 times time resolution of previous instruments.**



For more information on FOXSI Science see poster **P8.14**