A Low-Power, Radiation-Resistant Silicon-Drift-Detector Array for Extraterrestrial Element Mapping

Brian Ramsey

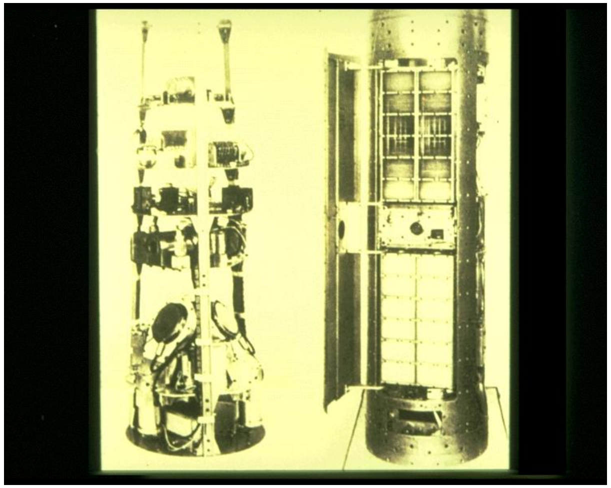
NASA MSFC, X-Ray Astronomy Group

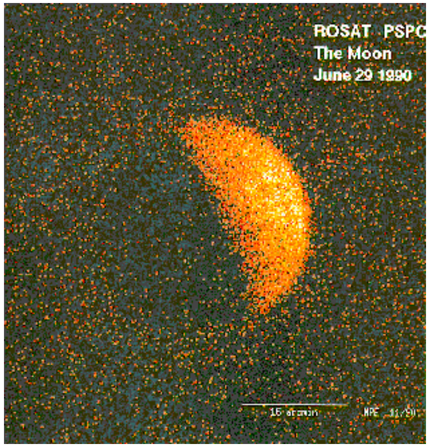
MSFC: Jessica Gaskin, Ron Elsner
BNL: Wei Chen, Gianluigi De Geronimo, Jeff. Keister, Shaouri Li, Zhen Li, David P. Siddons, Graham Smith

Background

Birth of X-Ray Astronomy

- **In 1962, Riccardo Giacconi and colleagues at AS&E flew sounding rocket to look at x-ray fluorescence from the moon**
- **Lunar signal was overshadowed by very strong emission from the Scorpious region**
- **Discovered the first extra-solar x-ray source, Sco X-1, and pervasive x-ray background**
- **This was the effective birth of x-ray astronomy**

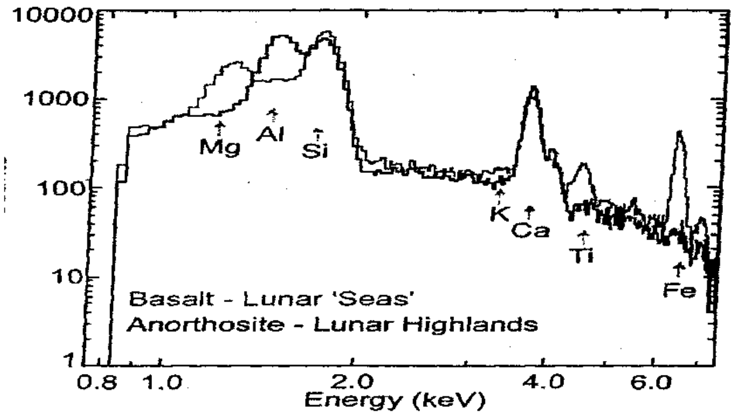




The German-led ROSAT mission took the first x-ray image of the moon in 1990

Introduction

- *Measurement of x-rays from the surface of objects can tell us about the chemical composition*
  - *Absorption of radiation causes characteristic fluorescence from material being irradiated.*
  - *By measuring the spectrum of the radiation and identifying lines in the spectrum, the emitting element (s) can be identified.*

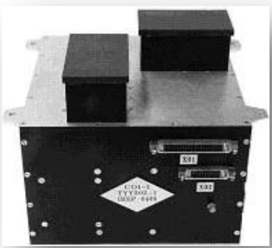


This technique works for any object that has no absorbing atmosphere and significant surface irradiation : Our Moon, the icy moons of Jupiter, the moons of Mars, the planet Mercury, Asteroids and Comets

Past Relevant Missions

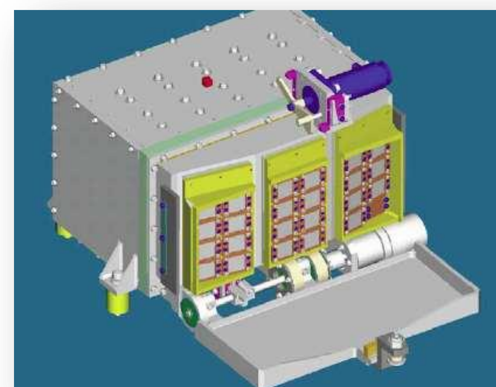
Kaguya (SELENE) [2007-2009]: Goal was to globally map (~90%) the lunar surface elemental composition using XRF-A, a CCD based instrument. The footprint resolution was 20km by 20km @100km with an energy resolution of <180eV @ Fe55 & -50^{o}C. Detector area is ***100cm^2*** (16 CCDs arrayed). ***This instrument sustained radiation damage, due to unexpected flight trajectory, detrimental to its performance.***[*]

http://www.selene.jaxa.jp/en/



Chang'E-1 [2007-2009]: Goal was to globally map the lunar surface major rock-forming elements Mg, Al, Si. Soft X-Ray Detector is ***1cm^2*** area Si-PIN diode, the energy resolution is <600eV @ Fe55, spatial resolution is 170kmx170km @ 200km altitude. Lack of solar activity has limited the results from this instrument.[ł]
Chang'E-2 [2010-2011+]: XRF results?

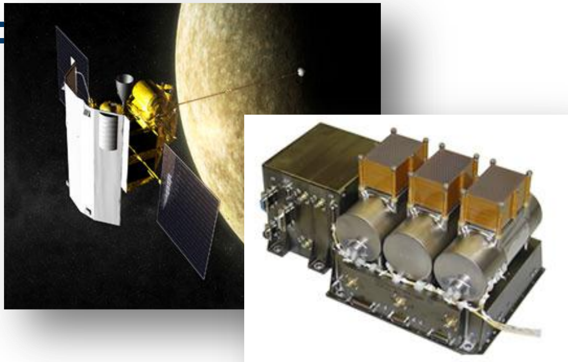
Chandrayaan-1 [2008-2009]: The goal of C1XS (swept charge device) was to map the lunar surface elemental composition (0.5-10keV range), at a 25km x 25km FoV @ 100km altitude and 50km x 50km @ 200km altitude. Geometric area is ***24cm^2***. Unlike D-C1XS, which had extensive radiation damage, C1XS was able to measure XRF spectra during solar flaring multiple times during its ~9 month operation. ***An Al-door was used to shield the detectors thru the Earth's radiation belts on its way to the Moon.*** "C1XS is the highest resolution, most accurately calibrated X-ray spectrometer flown to carry out global mapping of lunar chemistry."[‡]

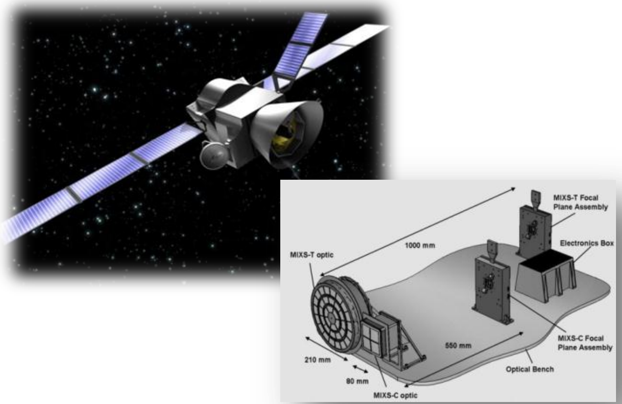


*Okada, T. *et al*., (2009). Trans. Japan Soc. for Aero. & Space Sci., Space Tech., ISTS 26, **7**: pp 39-42.
ł Huixian, S., *et. al*. (2008). Chin. J. Space Sci., **28**(5): pp 374-384.
‡ Narendranath, S., *et al.* (2011), Icarus, **214**(1): pp 53-66.

Relevant Missions

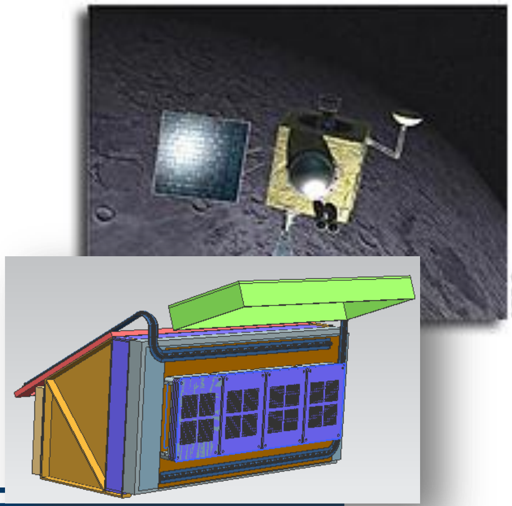
Messenger [2004-]: Goal is to map Mg, Al, Si, S, Ca, Ti, and Fe in the top millimeter of Mercury's crust. The XRS uses three gas proportional counters for this and also has a Si-PIN detector for monitoring solar activity. Spatial resolution will range from 42km to 3200km due to the highly elliptical orbit. The gas detectors have an active area of ***$30cm^2$***. A major disadvantage of gas detectors is their large backgrounds necessitating complex background rejection techniques.[ɣ]





BepiColombo [2014-]: Goal will be to globally map key elements (Mg, Al, Ca, Ti & Fe) on Mercury's surface using MIXS. MIXS detectors are Macropixel Active Pixel Sensor (SDD) DEPFET (DEpleted P-channel Field-Effect Transistor) arrays. Their energy resolution is 100 eV @ 1 keV. A collimator and focusing optics are used to define the fov. Footprint will be ~70-270km (MIXS-C) to < 1km (MIXS-T).

Chandrayaan-2 [2014]: Goal will be to map relevant elemental composition of the lunar surface during a solar flare. CLASS (Chandrayaan-2 Large Area Soft X-Ray Spectrometer) will use large area Swept Charge Devices similar to those on Chandrayaan-1. A spatial resolution of 25km FWHM @ 200km orbit is required. Total geometric area will be ***$64cm^2$***. As with C1XS, a door will be used to protect the detectors from radiation damage during transit.[8]



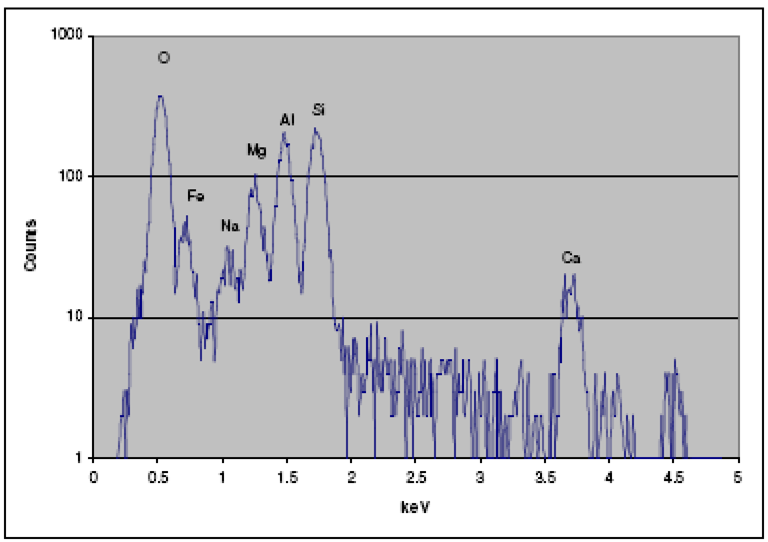
ɣ Schlemm II, C. E., *et. al*. (2007). Space Sci. rev., **131**: pp 393-415.
¥ Treis, J. *et al*., (2010). NIM A, **624**: pp 540-547.
8 Radhakrishna, V., *et al.* (2011). 42^{nd} LPSC Conf., #1708.

Lunar Instrument Configuration

Future Strawman Payload

Table 1: Lunar element mapper detector requirements

Total Area	500 cm^2
Energy Range	0.2 - 7 keV
Energy Resolution	$\leq$ 100 eV FWHM @ 0.28 keV
Radiation Hardness	> 10 krad
Power (including processing)	~ 10 Watts
Field of View (collimated)	10 deg x 10 deg



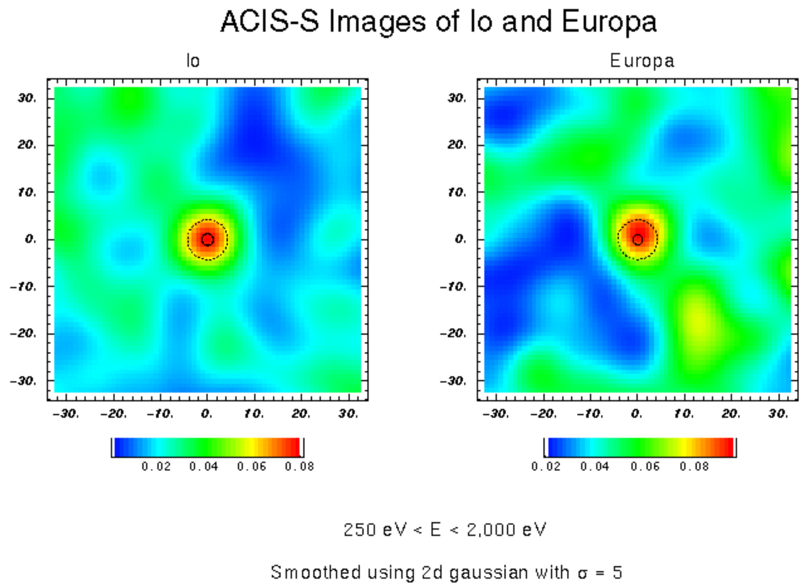
Simulation at left shows expected response for a 1 year integration at 50 km altitude in a footprint of 8.7 km x 8.7 km, using global abundances.

Expect to get better than 1% abundance sensitivity for all elements shown.

Assumes an active sun.

Jupiter Icy Moons Surface Analysis

- *The Chandra x-ray observatory detected x-ray emission from the moons of Jupiter in 2000: Oxygen K shell emission*

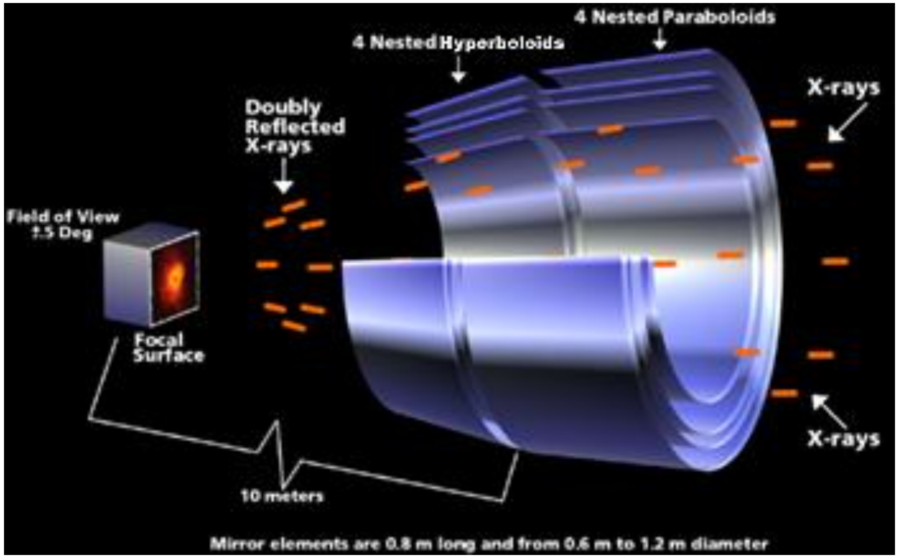


This emission is best explained by intense charged particle bombardment of the icy surface by energetic protons plus O and S ions .

Jupiter Icy Moons Surface Analysis

• *Jupiter Icy Moons Challenges : EXTREME ENVIRONMENT*

- *Use focusing x-ray optics to reduce overall data rate and increase signal to noise ratio…need array of small pixels*
- *Detectors must still be able to operate at very high rates, and be radiation resistant.*



Jupiter Icy Moons Surface Analysis

Focal Plane Detector Requirements

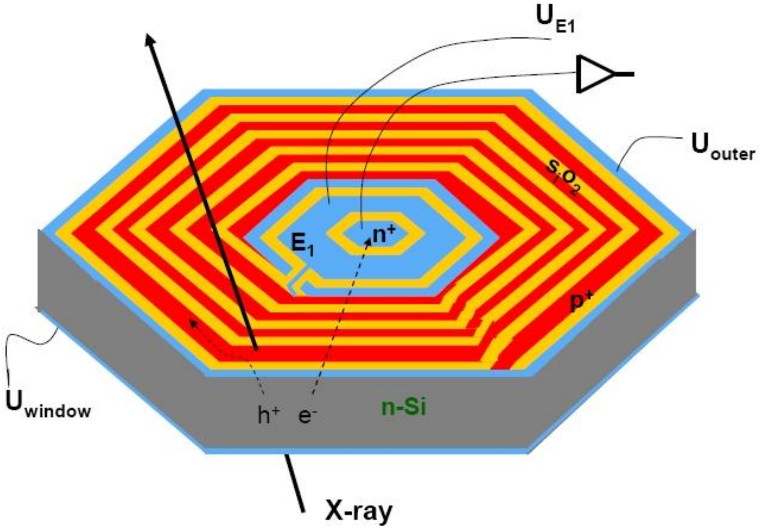
Area	~ 15 cm^2
Pixel size	Few mm
	0.2 - 7 keV
Energy Resolution	≤ 150 eV FWHM @ 0.28 keV
Count Rate Capability	10^6 counts / cm^2 sec
Radiation Hardness	Mrad
Power (including processing)	5 Watts

Table 3: Expected detection limits for elements on the surface of Europa and Io (see text)

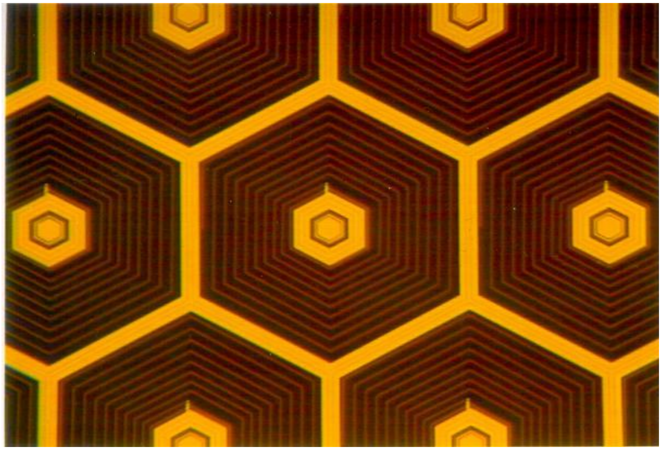
Element	Energy (keV)	Effective Area (cm^2)	% Abundance Relative to Oxygen	
			Europa	Io
Carbon	0.277	276	0.65	0.40
Nitrogen	0.392	275	0.35	0.22
Fluorine	0.677	263	0.15	0.09
Neon	0.849	189	0.16	0.09
Sodium	1.040	168	0.15	0.08
Magnesium	1.254	178	0.11	0.06
Aluminum	1.487	174	0.08	0.04
Silicon	1.740	156	0.08	0.04
Potassium	2.014	105	0.12	0.05
Sulfphur	2.308	70	0.18	0.06
Chlorine	2.622	62	0.18	0.05
Calcium	3.692	38	0.26	0.05
Iron	6.404	6.5	1.05	0.12

Solution

- *One type of detector can satisfy all the previous requirements .. An array of silicon drift detectors with custom readout electronics.*
  - *MSFC is working with Brookhaven National Laboratory to develop this type of instrument*
- *Single silicon wafers contain many individual detector elements (pixels)*
- *Each detector pixel has its own readout electronics channel – needs custom large scale integrated circuits*
  - *Individual pixel electronics gives very high rate capability*
  - *Low capacitance means good energy resolution*
  - *No clocking of charge packets so radiation resistant*
- Chen *et al.*, NSSC Record, IEEE 2007



Single pixel silicon drift detector schematic.

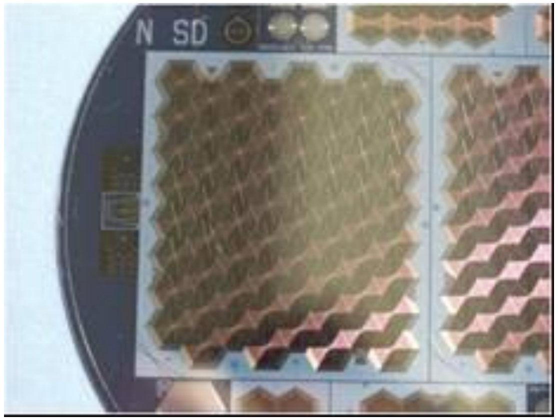


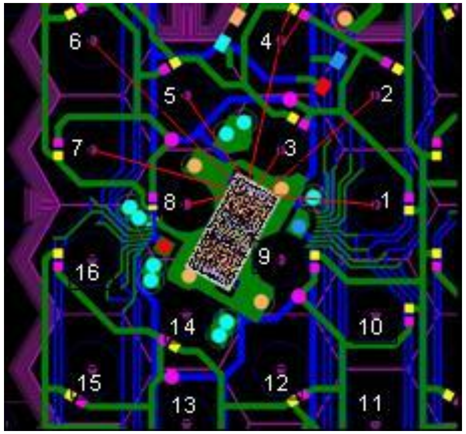
Drift detector array (with hexagonal pixels)

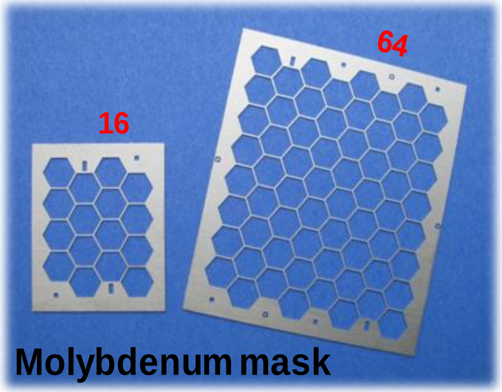
Solution

Geometry: Use a modular approach than can be easily tiled for large areas

- Basic unit of 64 SDD pixels , each ~ 5 mm diameter, in an 8 x 8 array covering ~ 13 cm^2
- SDDs are read out by 16-channel custom ASICS, (4 per module)
- Total power only 15 mW / cm^2 including sensor (processing power and cooling on top of this)





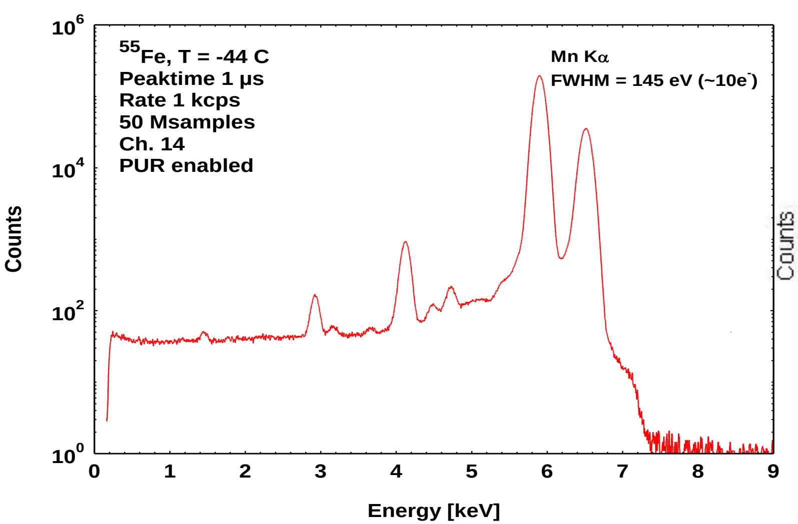


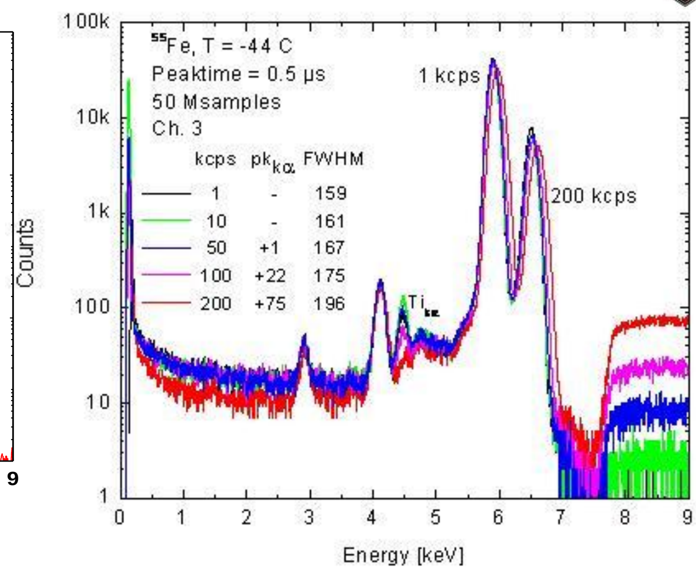
Project Status - Overall

• 3rd generation ASIC at foundry … modifications improve rate capability, noise levels and radiation hardness.

• Recent SDD work includes:

  • Double implant windows for improved low-energy response down to carbon line (0.28 keV).
  • Use of lower resistivity silicon to try to improve radiation hardness





Project Status – Radiation Hardness

Test at the Indiana University Cyclotron Facility Cyclotron – 200 MeV protons

- ASIC and diodes tested in Dec 2011
  - Series of doses up to 12 Mrad
- Full devices, ASIC + SDD tested in August 2011
  - Doses of 0.25 Mrad and 1.25 Mrad (3.10^{13} p / cm^2)
  - Second and third rounds of irradiation planned

Project Status – Radiation Hardness

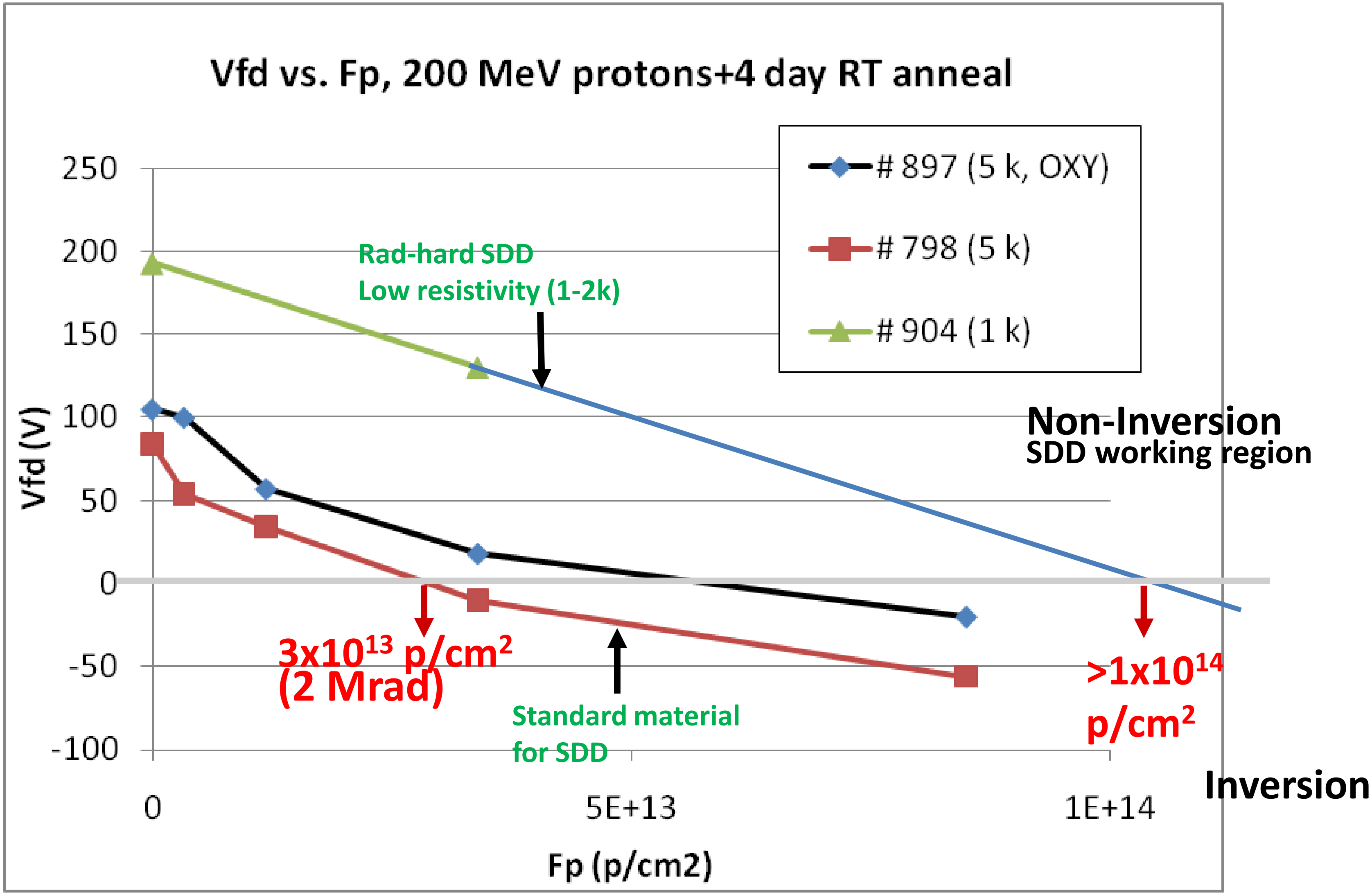
Complete Measurements on Radiated ASICS (w/o detector):

-- worst case at 2 Mrad (NMOS transistor has worst leakage around 2 Mrad in 0.25 um process)
-- radiation-sensitive paths have been located though simulation and analysis, and will be corrected in next fabrication.

	Rad level (Mrad)	Temperature	Peaking Time	0.25 us	0.5 us	1 us	2 us
	0.25	-50C	ASIC B-1-1	**Good**	**Good**	**Good**	**Good**
	0.6	-50C	ASIC B-2-1	**Good**	**Good**	**Good**	**Noisy**
	0.7	-50C	ASIC B-1-2	**Good**	**Noisy**	**Noisy**	**Noisy**
	1.0	-50C	ASIC B-2-2	**Good**	**Good**	**Noisy**	**Noisy**
w.c. →	**2.0**	-50C	ASIC B-1-3	**Good**	**Noisy**	**Saturated**	**Saturated**
	5.0	-50C	ASIC B-1-4	**Good**	**Good**	**Good**	**Saturated**
	8.0	-50C	ASIC B-2-3	**Good**	**Good**	**Good**	**noisy**
	12.0	-50C	ASIC B-2-4	**Good**	**Good**	**Good**	**Good**
	0.25	Room	ASIC B-1-1	**Good**	**Good**	**Noisy**	**Noisy**
	0.6	Room	ASIC B-2-1	**Good**	**Good**	**Noisy**	**Noisy**
	0.7	Room	ASIC B-1-2	**Good**	**Noisy**	**Saturated**	**Saturated**
	1.0	Room	ASIC B-2-2	**Good**	**Good/Noisy**	**Noisy/Saturated**	**Saturated**
w.c. →	**2.0**	Room	ASIC B-1-3	**Good**	**Saturated**	**Saturated**	**Saturated**
	5.0	Room	ASIC B-1-4	**Good**	**Good**	**Good**	**Saturated**
	8.0	Room	ASIC B-2-3	**Noisy**	**Noisy**	**Noisy**	**Saturated**
	12.0	Room	ASIC B-2-4	**Noisy**	**Noisy**	**Noisy**	**Saturated**

2nd generation ASIC tested above. 3rd generation expected to give good performance at 1 Mrad, 1 usec

Project Status – Radiation Hardness

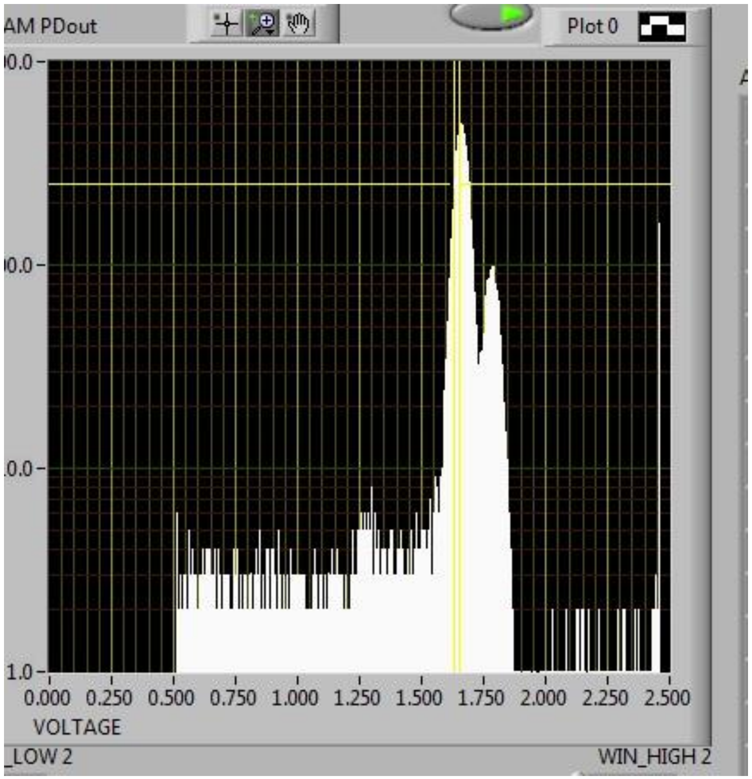


Project Status

0.25 Mrad dose on SDD + ASIC

Rate	FWHM(eV)
50 kcps	254

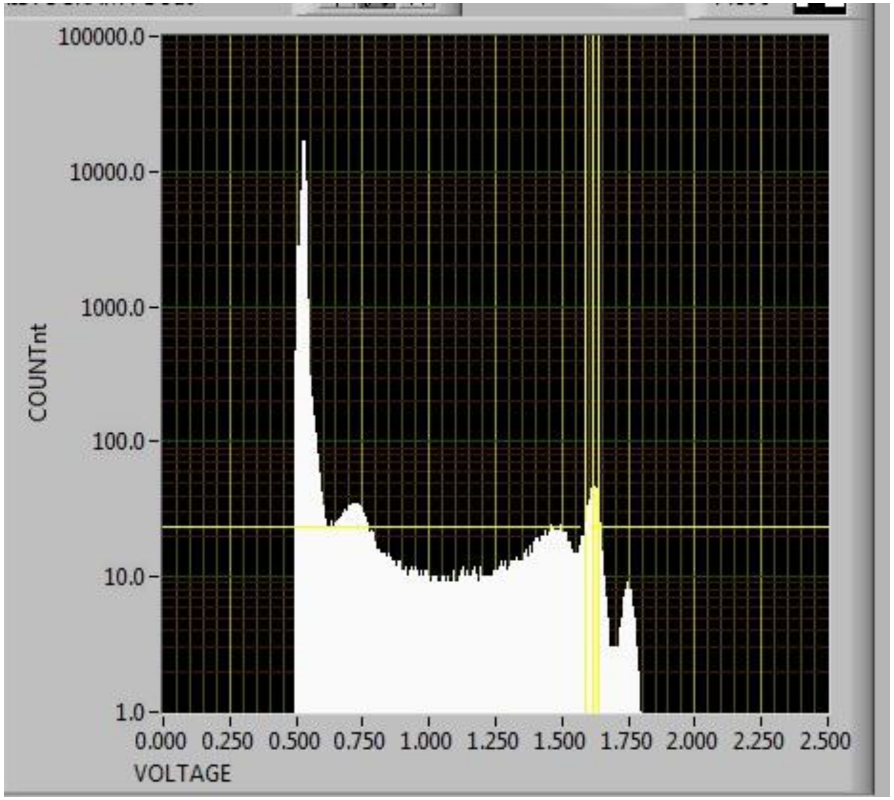
Fe^{55} @ -75 ºC



1.25 Mrad dose on SDD + ASIC

Rate	FWHM (eV)
25 kpcs	230

Fe^{55} @ -75 ºC



Project Status

1.25 Mrad dose clearly degraded the detector significantly – very large continuum and small photopeak (preliminary data [Sep 9, 2011]-- very sensitive to bias conditions)

- Inversion cannot have taken place at 1.25 Mrad with this resistivity

- Probable explanation is charge trapping due to radiation damage

V_{BW} (V)	V_{E2} (V)	V_{OR} (V)	E_{dr} (V/cm)	Drift time t_{dr} (μs)	Charge cloud due to Diff x (μm)	Dt (ns)
-220	-18	-105	368	0.18	34	2.4

Trapping time at 1 Mrad: $\tau_t = \left(5\times10^{-7}\cdot\Phi_{eq}\right)^{-1}\ (\mathrm{s}) = 0.12\,\mu\mathrm{s}$

Total drift time larger than trapping time

Project Status

Conclusion:

• We have developed a silicon drift detector and custom ASIC for element mapping around remote bodies.

• The device is very low power and its modular form can be scaled to any desired area for use with a simple collimator or at the focus of a mirror system.

• Radiation resistance:

  • It is expected that the 3rd iteration custom ASIC will be able to comfortably handle > 1 Mrad.

  • The low-resistivity SDDs function to 0.25 Mrad, but degrade significantly at 1.25 Mrad. The mechanism for this is under investigation.