Soft x-ray spectrometer (SXS): the high-resolution cryogenic spectrometer onboard *ASTRO-H*

Kazuhisa Mitsuda[a], Richard L. Kelley[i], Hiroki Akamatsu[m], Thomas Bialas[i], Kevin R. Boyce[i], Gregory V. Brown[l], Edgar Canavan[l], Meng Chiao[l], Elisa Costantini[m], Jan-Willem den Herder[m], Cor de Vries[m], Michael J. DiPirro[i], Megan E. Eckart[l], Yuichiro Ezoe[c], Ryuichi Fujimoto[d], Daniel Haas[m], Akio Hoshino[d], Kumi Ishikawa[h], Yoshitaka Ishisaki[c], Naoko Iyomoto[o], Caroline A. Kilbourne[i], Mark Kimball[i], Shunji Kitamoto[g], Saori Konami[c], Maurice A. Leutenegger[l], Dan McCammon[j], Joseph Miko[l], Ikuyuki Mitsuishi[p], Hiroshi Murakami[t], Masahide Murakami[e], Hirofumi Noda[h], Mina Ogawa[a], Takaya Ohashi[c], Atsushi Okamoto[b], Naomi Ota[q], Stéphane Paltani[n], F. Scott Porter[i], Kosuke Sato[r], Yoichi Sato[b], Makoto Sawada[s], Hitomi Seta[f], Keisuke Shinozaki[b], Peter J. Shirron[i], Gary A. Sneiderman[i], Hiroyuki Sugita[b], Andrew Szymkowiak[k], Yoh Takei[a], Toru Tamagawa[h], Makoto S. Tashiro[f], Yukikatsu Terada[f], Masahiro Tsujimoto[a], Shinya Yamada[c], Noriko Y. Yamasaki[a]

[a]Institute of Space and Astronautical Science, JAXA, Sagamihara, Japan; [b]Aerospace Research and Development Directorate, JAXA, Tsukuba, Japan; [c]Tokyo Metropolitan University, Hachioji, Japan; [d]Kanazwa University, Kanazawa, Japan; [e]Tsukuba University, Tsukuba Japan; [f] Saitama University, Saitama, Japan; [g]Rikkyo University, Tokyo, Japan; [h] Riken, Wako, Japan; [i]NASA/Goddard, Greenbelt, MD, USA; [j]Univ. of Wisconsin, Madison, WI, USA; [k] Yale Univ. New Haven, CT, USA; [l] Lawrence Livermore National Laboratory, Livermore, CA, USA; [m]SRON Netherlands Institute for Space Research, Utrecht, Netherlands; [n]Geneva University, Geneva, Switzerland [o]Kyushu University, Japan [p]Nagoya University, Japan [q]Nara Women's University, Japan [r]Tokyo University of Science , Japan [s]Aoyama Gakuin University, Japan [t]Tohoku Gakuin University, Japan

ABSTRACT

We present the development status of the Soft X-ray Spectrometer (SXS) onboard the *ASTRO-H* mission. The SXS provides the capability of high energy-resolution X-ray spectroscopy of a FWHM energy resolution of $< 7eV$ in the energy range of 0.3 – 10 keV. It utilizes an X-ray micorcalorimeter array operated at 50 mK. The SXS microcalorimeter subsystem is being developed in an EM-FM approach. The EM SXS cryostat was developed and fully tested and, although the design was generally confirmed, several anomalies and problems were found. Among them is the interference of the detector with the micro-vibrations from the mechanical coolers, which is the most difficult one to solve. We have pursued three different countermeasures and two of them seem to be effective. So far we have obtained energy resolutions satisfying the requirement with the FM cryostat.

Keywords: X-ray astronomy, Soft X-ray, High resolution X-ray Spectroscopy

1. INTRODUCTION

The Soft X-ray Spectrometer (SXS) is the main instrument of *ASTRO-H*[1] providing the capability of high energy-resolution X-ray spectroscopy in 0.3 – 10 keV.[2] It consists of X-ray focusing mirrors (SXS-SXT, also called as SXT-S) and the X-ray micro-Calorimeter Spectrometer system (SXS-XCS, sometimes simply called SXS) and is developed by international collaboration lead by JAXA and NASA with European participation. The X-ray detector is a 6×6 format microcalorimeter array operated at a cryogenic temperature of 50 mK and covers a $3' \times 3'$ filed of view of the X-ray telescope of 5.6 m focal length. The requirement for the energy resolution is

Further author information: Send correspondence to K.M: E-mail: mitsuda@astro.isas.jaxa.jp

Space Telescopes and Instrumentation 2014: Ultraviolet to Gamma Ray, edited by Tadayuki Takahashi,
Jan-Willem A. den Herder, Mark Bautz, Proc. of SPIE Vol. 9144, 91442A · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2057199

Table 1. *ASTRO-H* SXS key requirments

	Requirement	Goal
Energy range	0.3 - 12 keV	
Effective area at 1 keV	160 cm^2	
Effective area at 6 keV	210 cm^2	
Energy resolution	7 eV	4 eV
Array format	6×6	
Field of view	$2.9' \times 2.9'$	
Angula resolution	1.7'(HPD)	1.3' (HPD)
Lifetime	3 years	5 years
Time assignment resolution	80 μs	
Maximum counting rate	150 c s^{-1} $pixel^{-1}$	
Energy-scale calibration accuracy	2 eV	1 eV
Line-spread-function calibration accuracy	2 eV	1 eV

Table 2. *ASTRO-H* SXS key design parameters

Parameter	Value
SXS XRT (SXT-S, Thin-foil mirrors)*	
Focal length	5.6 m
Diameter of most outer mirror	45 cm
Reflecting surface	Gold
Thermal shield	Al (300 nm) + PET (0.22 μm) with SUS mesh of a 94 % open fraction
SXS XCS (6×6 microcalorimeter array)	
Operating temperature	50 mK
Pixel size	814 μm $\times$814μm
Pixel pitch	832μm
Field of view	3'.05 $\times$ 3'.05
X-ray absorber	HgTe, 8μm thickness
Optical Blocking filters	5 filters, polyimide (460 nm) + Al (400nm) total, Si mesh on two filters

* See Okajima et al. (2008)[3] for more details of the mirror design.

7 eV (FWHM) with a goal of 4 eV. The requirements for other parameters are summarized in Table 1, while the design values are shown in Table 2. The filter wheel mechanism (FWM) is inserted in between the SXT-S and the detector system, in order to reduce X-ray flux when necessary, and to provide calibration X-rays at a predetermined time efficiency.

The detector is cooled to 50 mK by four stage cooling system (Figure 1). A temperature of 50 mK is obtained by the double-stage adiabatic de-magnetization refrigerator (dADR) which is precooled by superfluid liquid He (LHe) at 1.2 K. The He tank is surrounded by thermal shields which are cooled by two different types of mechanical coolers; the ^{4}He JT cooler providing a 4.5 K thermal shield, and two sets of double-stage Stirling-Cycle coolers (2ST) providing $\sim$ 20 K and $\sim$ 100 K shield temperatures. The JT cooler uses other two sets of 2ST's as is pre-cooling. The system has redundancy down to 1.2 K. The third stage ADR is not used in nominal operation. After all LHe is exhausted, the JT and three-stage ADR system works as cryogen-free cooling system.

The cryostat of the SXS-XCS being developed in EM/FM approach; i.e. we have developed a fully functional engineering model consisting of the Dewar, the detector system, X-ray aperture, and the full cooling chain. In the EM/FM approach, we intended to verify the the complex four-stage cooling chain, and the performance of the X-ray microcalorimeter under the mechanical (micro-vibration) and radiation (electro-magnetic interference)

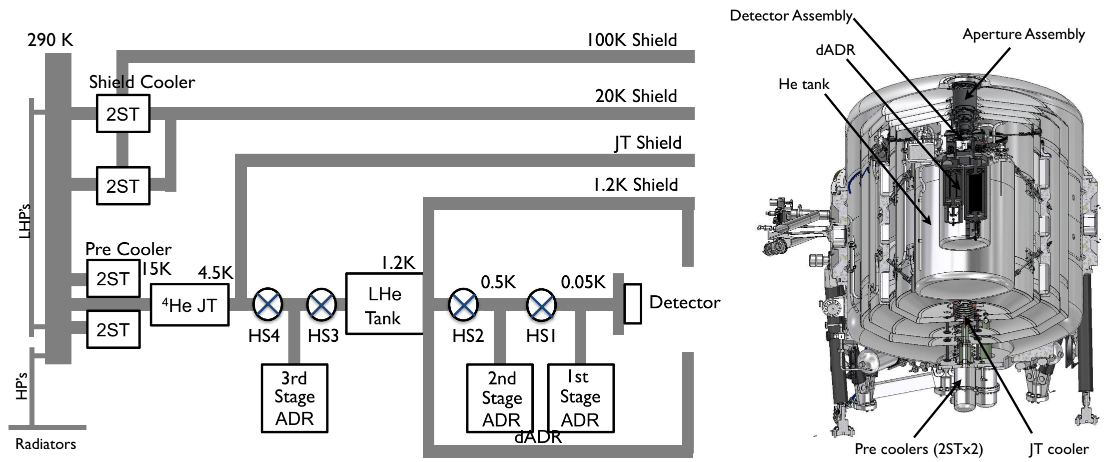

Figure 1. Block diagram of the *ASTRO-H* SXS cooling chain (left) and the cut-away view of the Dewar 3D CAD design (right).

environment with the EM, and to improve in the FM, if we find necessary.

We have completed assemble of EM cryostat in August 2012 and performed various SXS-XCS subsystem-level test until March 2013. We have found several problems in the EM Dewar, among which the micro-disturbance from the compressors of the 2ST coolers problem seemed to be most difficult to solve. We are now in the middle of the FM cryostat assemble, and testing the countermeasures for the micro-vibrations. In this paper, we will describe the EM test results and present status of the FM cryostat.

2. EM TEST RESULTS

In the first cool down test of the EM Dewar in which the He tank was brought to Liquid He temperature (4.2K), we noticed that the Heat Switch 2 (HS2 in Figure 1) was always off although it should have been on when the getter pump of the heat switch is above a certain temperature. We consider that the He gas encapsulated inside HS2 was lost. Then when we brought the He to superfluid, we observed "He puffs" which are signature of super leak from He tank or He plumbing system. Since it takes a long time to open the Dewar by disintegrating the 100 layers of MLI, to fix the problem, and to integrate the Dewar again, we decided not to fix the problems and to find workaround solutions so that we can continue testing. Of course we also need to fix the problems in the FM cryostat and to establish a Dewar integration plan so that we can find any problem, before completing the installation of the multi-layer insulation.

In November 2012, we successfully operated the dADR and obtained 50mK. During recycle of 2nd stage ADR, we used the Dewar guard vacuum as a heat switch instead of HS2; we dosed in a small amount of He in the Dewar guard vacuum when we needed thermal contact between the He tank and the 2nd stage of ADR, then we evacuated Dewar guard vacuum again, when we would like to turn off the thermal contact.[4]

Then found that the performance of the X-ray microcalorimeters is strongly affected by the operation of mechanical coolers. In Figure 2 , we show the FWHM energy resolution as a function of temperature fluctuation observed in the thermometer which is measuring the temperature of the calorimeter thermal sink (CTS).

We performed several different tests, in order to find how the mechanical coolers are affecting the calorimeter performance. We show an example of results in Figure 3. In this test, the ADR temperature control was set to off and the temperature of the CTS was gradually increasing because of parasitic heat load. All mechanical coolers were turned off except for the time period shown in the figure. In the first half of the time, the main shell of the Dewar was vibrated from outside by an accelerator (stinger). When the vibration frequency comes to certain values (140, 210, and 290 Hz in this figure), we observed a sharp increase of the CTS temperature. When we turn on a mechanical cooler, we observe increase of the CTS temperature and increase of its time variation. The pulse height of the calorimeter signal decreases when the CTS temperature increases, which is expected.

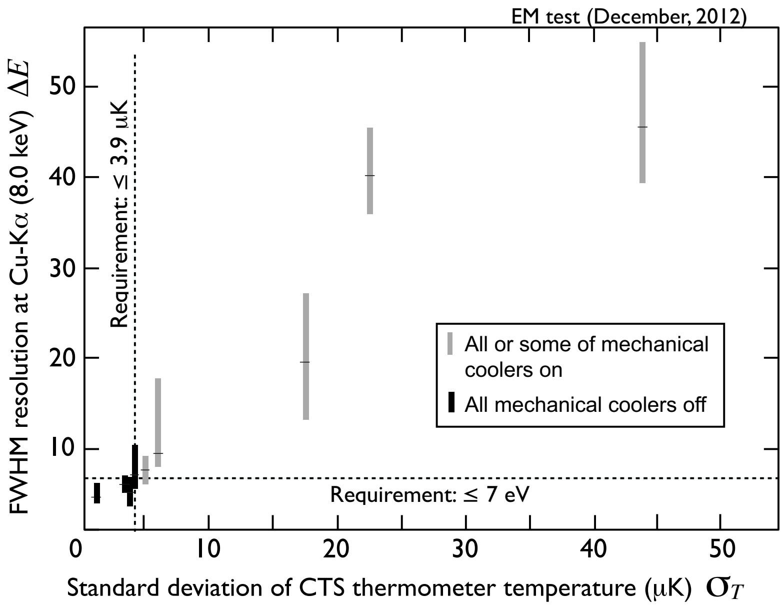

Figure 2. FWHM energy resolution as temperature read-out fluctuation of the calorimeter thermal sink (CTS) observed in the EM subsystem test. The vertical bars show the range of the resolution across the array. When all the mechanical coolers are off, both the resolution and the temperature fluctuation are almost within the requirements.

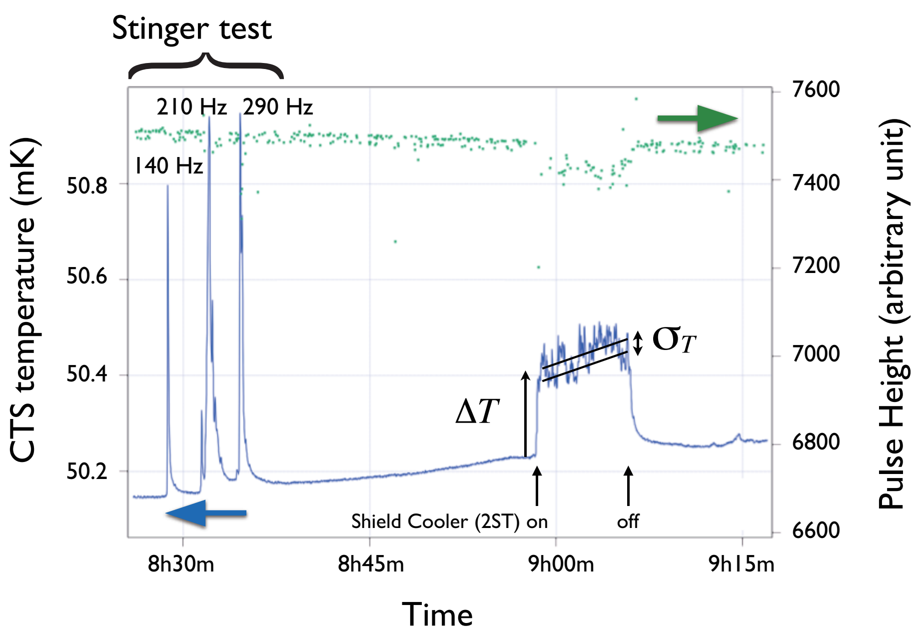

Figure 3. Example of the EM test data. Dots show the pulse height of X-ray event form Cu Kα line (scale on the right) and the line show the CTS temperature (scale on the left).

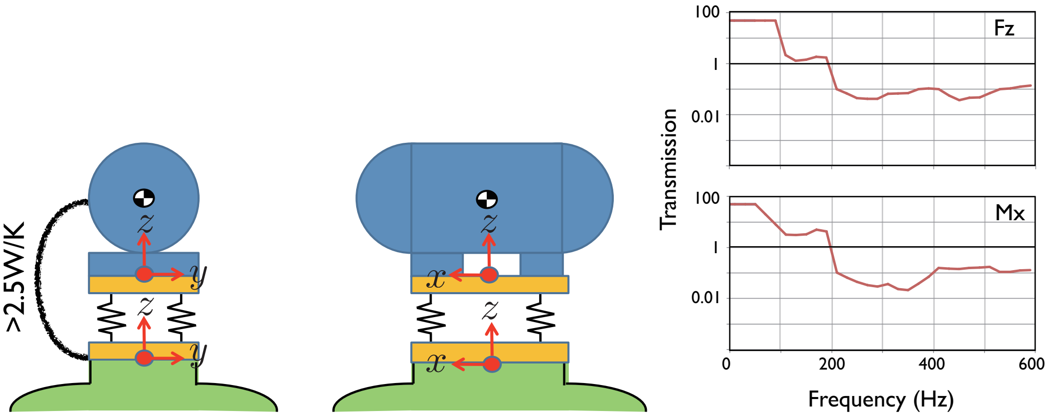

Figure 4. Schematic view of an Isolator (left) and example of isolation requirement (right). The isolator is essentially a spring system that reduces vibration propagation above the resonant frequency. Heat dissipated from the compressor must be partly dumped on to the Dewar main shell, and we need a thermal strap. The isolation requirement is given in 6 degrees of freedom; force in three directions and torques in three axes.

From these experiments and subsequent micro-vibrations measurement of the 2ST coolers , we obtained the following conclusion.

(a) The energy of micro-vibrations from the compressors of 2ST coolers is somehow converted into heat at or near the CTS,

(b) There are several frequencies at which the CTS is sensitive,

(c) Originally we intended to adjust the drive frequency of the cooler in order to avoid the frequency match, however, the CTS is susceptible to the vibration which has continuum frequency spectrum Thus the changing drive frequency does not work.

3. FM DESIGN AND TEST STATUS

Towards the FM design we first defined the requirement for the effect of the micro-vibrations by the CTS temperature fluctuation:

$$\sigma^2_{T(\mathrm{CTS})}(\mathrm{on}) - \sigma^2_{T(\mathrm{CTS})}(\mathrm{off}) < (3.2\ \mu\mathrm{K})^2 \tag{1}$$

Then we considered countermeasures according to the three basic ideas; (1) to reduce the continuum component of micro-vibrations from the compressors, (2) to reduce the propagation of the micro-vibrations from the compressors to the CTS, and (3) to reduce the susceptibility of the detector system against the micro-vibrations.

Presently the FM Dewar is still in fabrication. However, in order to avoid finding any anomalies after closing all MLI's of the Dewar, we already performed the first cool down test with fully functional detector system. In the following we summarize the details of the countermeasures and their present verification status.

(1) To reduce the continuum component of micro-vibrations from the compressors:
We have identified the source of the continuum component in the compressor and modified its design. As the result, micro-vibrations was reduced and the CTS temperature fluctuation came down to marginally acceptable level according to Equation (1). However, we concluded that we did not have enough time to prove the reliability of the new design and thus we will not adopt in the FM design. The micro-vibrations levels observed with the new compressors was utilized to define the requirement for the isolators (see below).

Table 3. Example results of an EM isolator with FM SXS cryostat

SC-A compressor	All others	σ_T	FWHM resolution
Direct mount	isolated	0.53 μ K	6.4 eV
EM isolator	isolated	0.49 μ K	6.0 eV
power off	isolated	0.45 μ K	*

* SC-A is one of the shield coolers.

* No measurement.

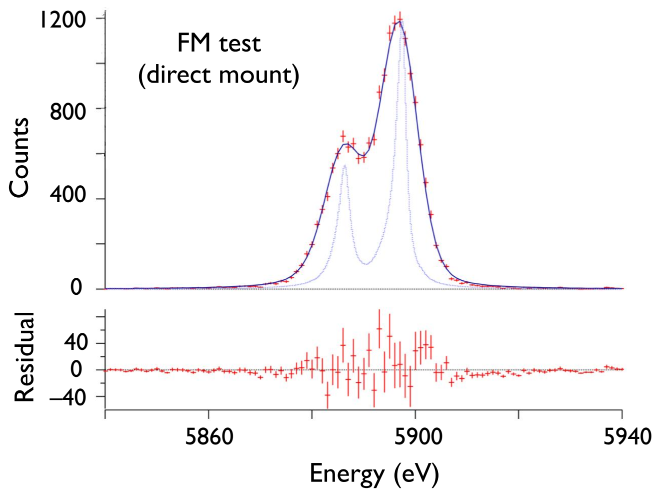

Figure 5. The energy spectrum of Mn K_α line obtained for the calibration pixels during the FM subsystem test. The FWHM energy resolution of this pixel was estimated to be 6.6 eV.

(2) To reduce the propagation of micro-vibrations from the compressors to the CTS:
A vibration isolator between the compressor and the Dewar main shell is being investigated. The Schematic view of an Isolator and isolation requirements for Z-direction force (F_z and X-axis torque (M_x) are respectively shown as example. Isolator should have a response larger than unity below its resonant frequency. The requirement for this low frequency level is determined by the mechanical environment during the launch and ground testing at the isolator attachment point, and the tolerance of the compressor against the mechanical loads.
Engineering model isolators have been fabricated and are presently being tested. One of the EM isolator was attached to the FM Dewar and tested. Because the calorimeters are less sensitive to the micro-vibrations (see below) in FM, the effect of the isolator is not very large. However, we still cold observe the both improvement of the energy resolution and reduction of the CTS temperature fluctuation by the isolator (Table 3).

(3) To reduce the susceptibility of the detector system against the micro-vibrations:
Although we could not reduce heat generation by micro-vibrations, it was found that the heat conductance between the 1st stage ADR and the CTS can be improved by a factor of ~ 8. Then the temperature fluctuation is expected to be reduced by a factor of ~ 8 for the same heat input and fluctuation. We find that the temperature fluctuation may be reduced to near the requirement even for the worst case of Figure 2, We confirmed this with the FM subsystem test. Even when all the compressors are directly mounted on the Dewar without any isolator, the CTS temperature fluctuation was in a range of 1.5 – 2.0 μK and an energy resolution of 6.6 eV was obtained for the calibration pixel.

Presently, our baseline is to adopt both (2) and (3), although for the final decision for (2), we have to wait for the low frequency response of the isolator, which is being tested now experientially.

ACKNOWLEDGMENTS

We are grateful to the engineers in Sumitomo Heavy Industries (SHI), in NASA/GSFC, in Mitsubishi Heavy Industries (MHI), in SRON, and in Geneva University, and scientists and engineers in JAXA and univrsities for the design of the SXS microcalorimeter system, and graduate students who contributed laboratory experiments and design; especially K. Kanao, S. Yoshida, M. Miyaoka, K. Narasaki, S. Tsunematsu, T. Hiroishi, A. Okabayashi, K. Ootsuka (SHI), J. Adams, P. Arsenovic, T. Croffroad, P. Goodwin, T. Hait, J. Kazeva, R.l Martinez, C. Masters, D. McGuinness, S. Moseley, T. Muench, J. Pontius, Q. Prather, K. Ray, D. Robinson, G. Rosanova, M. Sampson, M. Sansebastian, J. Savinell, A. Schweiss, S. Shuman, C. Simmons, R. Szymkiewicz, T. Watanabe, M. Windhausen, (NASA/GSFC), K. Masukawa, K. Matsuda, Y. Kuroda (MHI), H. Aarts, M. Frericks, P. Laubert, P. Lowes (SRON), R. Dubosson (Geneva), M. Nomachi (Osaka University), K. Ishimura, N. Iwata, T. Kawano, K. Minesugi, H. Ogawa, (ISAS/JAXA), S. Yasuda, (ARD/JAXA) Y. Shimoda, S. Takeda, T. Yasuda, M. Asahina (Saitama University), and T. Yuasa (Riken). We would also like to thank members of Akari and SPICA teams, in particular, T. Nakagawa, and the SMILES group at ISAS/JAXA for the collaboration of mechanical cooler development.

REFERENCES

[1] Takahashi, T. and et al., "The ASTRO-H X-ray astronomy satellite," *Proc. SPIE* **9144**, 9144–76 (2014).

[2] Mitsuda, K. and et al., "he High-Resolution X-Ray Microcalorimeter Spectrometer, SXS, on Astro-H," *J. of Low Temp. Phys.* **167**, 795 (2012).

[3] Okajima, T. and et al., "Soft x-ray mirrors onboard the NeXT satellite," *Proc. SPIE* **7011**, 70112X–70112X–10 (2008).

[4] Shirron, P. and et al., "Operation of an ADR using helium exchange gas as a substitute for a failed heat switch," *Cryogenecs.* **in press** (2014).