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# Evolution of X-ray Calorimeter Spectrometers at the Lawrence Livermore Electron Beam Ion Trap

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**Abstract.** High-resolution broadband, non-dispersive x-ray calorimeter spectrometers have been under development for spaceflight since 1984. As an offshoot of the significant NASA investment in this technology, we have developed a series of calorimeter instruments for laboratory use and installed them at the Electron Beam Ion Trap (EBIT) facility at the Lawrence Livermore National Laboratory. The calorimeter instruments at EBIT have significantly enhanced the capabilities of our laboratory astrophysics program including broad-band measurements of emission from charge exchange recombination and absolute cross sections for collisional excitation. The first Goddard Space Flight Center (GSFC) calorimeter instrument was installed at the EBIT facility in July of 2000 and has seen two major upgrades. The performance of the instrument has significantly improved from the initial instrument that had a resolving power of ~500 at 6 keV, and essentially no quantum efficiency at energies above 20 keV, to the current instrument that has a resolving power of 1350 and 95% quantum efficiency at 6 keV, and a resolving power of 1800 and 32% quantum efficiency at 60 keV.

## 1. Introduction

X-ray Calorimeter detectors have been in development since 1984 for use in non-dispersive spectrometers for astrophysics. Spaceflight calorimeter instruments use pixelated detectors that are broad-band, high resolution, and have nearly 100% quantum efficiency. The detector arrays are quite small with the current state-of-the-art still less than 1000 pixels. However, since each detector pixel is an independent spectrometer, the detectors are true spatial-spectral instruments. For astrophysical sources this is very important. Dispersive instruments for x-ray astrophysics are generally much less efficient and are typically slit-less spectrometers, relying on the source to limit the divergence of the beam onto the dispersing elements. Thus the dispersive spectrometers degrade rapidly when the source extends more than a few arcminutes. This limits the value of dispersive instruments for extended astrophysical sources such as supernova remnants, galaxies, clusters of galaxies, and the interstellar medium, all objects with rich spectral structure that would benefit substantially from high-resolution measurements. An x-ray calorimeter instrument is a self-contained spectrometer with no external optical components and can be placed directly at the focus of an x-ray telescope. Its performance is not limited by the spatial properties of the source. These characteristics make the calorimeter instrument highly attractive for x-ray astrophysics, and even though the instruments are large, require relatively large amounts of electrical power, and are complex, they are likely to be included on every major x-ray observatory for the foreseeable future including *Astro-H, Spectrum-Roentgen-Gamma, and the International X-ray Observatory*. During

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the last 8 years we have leveraged this extensive investment in high performance non-dispersive x-ray spectrometers to aid our laboratory astrophysics program that is centered around the Electron Beam Ion Trap (EBIT) at the Lawrence Livermore National Laboratory (LLNL).

**Table 1.** Calorimeter spectrometers at the LLNL EBIT. In each column the first values are for the low/midband pixels and the second values are for the high-energy pixels in the detector array.

| | **XRS/EBIT v1** | **XRS/EBIT v2** | **ECS** | **TEMS** |
|---|---|---|---|---|
| Operation (year) | 2000-2003 | 2003-2007 | 2007-- | 2010 |
| Array size | 32 pixels<br>none | 28 pixels<br>4 pixels | 16 pixels<br>14 pixels | 256 pixels<br>64 pixels |
| Pixel size | 0.64x0.64 mm | 0.64x0.64 mm | 0.64x0.64 mm | 0.3 x 0.3 mm<br>1.0 x 1.0 mm |
| Spectral resolution (FWHM) | 11.5 eV @ 6 keV | 6 eV @ 6 keV<br>70-150eV @ 60keV | 4.5 eV at 6 keV<br>32 eV @ 60keV | 0.8 eV @ 1 keV<br>2.0 eV @ 6 keV<br>30 eV @ 60 keV |
| Quantum efficiency | 95% @ 6 keV | 95% @ 6 keV<br>10% @ 60 keV | 95% @ 6 keV<br>32% @ 60 keV | 95% @ 6 keV<br>60% @ 60 keV |
| Operating temp. | 60 mK | 60 mK | 50 mK | 50 mK |
| Band pass | 0.1-12 keV | 0.1-12 keV<br>0.5-60 keV | 0.1-12 keV<br>0.5-100 keV | 0.1-12 keV<br>0.5-200 keV |
| Detector time constant | 9 ms | 3 ms<br>10 ms | 3 ms<br>40 ms | 0.3 ms<br>< 5 ms |

## 2. The EBIT calorimeter instruments

An x-ray calorimeter operates as a single photon thermal spectrometer [1]. The device absorbs each x-ray in a high quantum efficiency absorbing material and then measuring the temperature rise after the photoelectron has thermalized in the material using a very sensitive thermometer. Using low heat capacity materials, very low temperatures (< 100 mK), and sensitive thermometers, spectrometers with resolving powers of over 2000 with a broad dynamic range have been constructed.

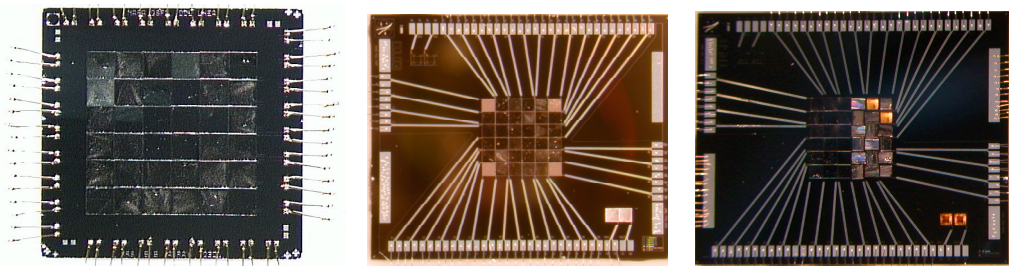

**Figure 1.** The 32 pixel detector arrays for the three generations of EBIT calorimeters. From left to right: the XRS/EBIT v1, The XRS/EBIT v2, and the ECS. The four corners of the middle array and the left side of the right array are high-energy detector pixels.

We have sequentially deployed three calorimeter instruments at the EBIT facility at Lawrence Livermore National Laboratory (LLNL) primarily for our laboratory astrophysics program (see [2] and references therein). The calorimeter instrument complements higher spectral resolution dispersive spectrometers at the EBIT facility by providing broad-band contextual information to the narrow band dispersive instruments. In addition, the calorimeter instruments are extremely efficient, allowing experiments to be performed that would be prohibitive using the dispersive instruments in the laboratory alone. Our laboratory astrophysics program concentrates on benchmarking the atomic codes used in the spectral synthesis models that form the basis for interpreting astrophysical observations. This includes, for example, measurements of line ratios, cross sections, and line identification in collisional excitation and charge exchange recombination.

The calorimeter spectrometers at EBIT are summarized in Table 1 and the detector arrays for each instrument are shown in Figure 1. The first generation spectrometer (XRS/EBIT v1) used a spare detector array and an engineering model focal plane assembly from the Astro-E observatory [3]. The array is composed of 32 pixels in a square 6 x 6 geometry (the corner pixels are not read-out) with a 0.64 mm pitch. The absorber material is 8 μm of HgTe, a material that is a compromise between fast thermalization and low heat capacity. The thermometers are formed *in-situ* on the silicon substrate of the array by ion implantation directly into each pixel. The pixels and their thermal isolation structures are then defined using wet chemical etching. The v1 instrument had a Gaussian instrumental response with a spectral resolution of 11.5 eV full width at half maximum (FWHM) and a quantum efficiency of 95% at 6 keV, and a simultaneous bandpass from 0.1 to ~12 keV. The instrument was first deployed in July of 2000 and ran almost continuously until it was upgraded in 2003 as described below.

The second generation instrument (XRS EBIT v2) is based on an improved version of the ion-implanted detectors from the Astro-E instrument described above [4]. The improvements were part of the development program for the Astro-E2 (Suzaku) observatory that was launched in 2005. The basic improvements were in the noise performance of the implanted thermometers and a switch from wet etching to reactive ion etching in defining the individual pixels and their thermal and mechanical support structures in the array to improve the reproducibility and the mechanical robustness of the detector. The performance of the v2 instrument is significantly enhanced. The spectral resolution of the detector improved by a factor of two to 6 eV FWHM at 6 keV. In addition, we implemented four pixels with increased quantum efficiency at high energies by using 30 μm of Bi in place of the 8 μm of HgTe in the x-ray absorber. This improved the QE at 60 keV from 3% to about 10%. Unfortunately the spectral resolution of these early high-energy detectors was between 70 and 150 eV at 60 keV, limiting their utility.

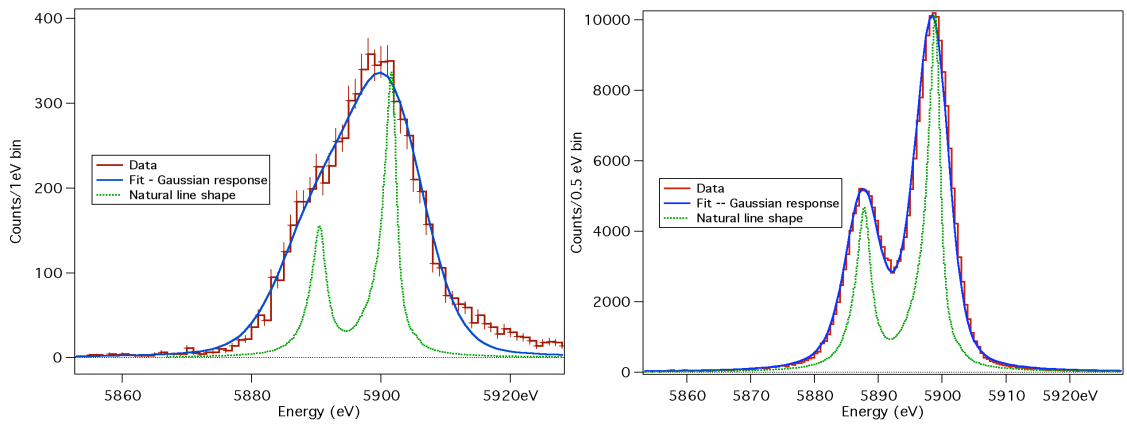


**Figure 2.** Mn $K_\alpha$ emission from a $^{55}$Fe radioactive source as measured by the XRS/EBIT v1 (left) with a resolution of 11.5 eV FWHM and with the ECS (right) with a resolution of 4.5 eV FWHM.

Both the v1 and the v2 XRS/EBIT instruments used the same cryogenic assembly consisting of a 14 liter liquid helium tank pumped to 1.5 K, a liquid nitrogen thermal shield, and a single stage adiabatic demagnetization refrigerator (ADR) to cool the detector array to its operating temperature of 60 mK. The focal plane assembly itself was, in both cases, an engineering model unit from the Astro-E flight program. The ADR and dewar were assembled quickly from spare parts in order to field the instrument as cheaply and quickly as possible. The infrastructure, including the analog and digital readout electronics, was composed largely of engineering model and ground support equipment from the Astro-E flight program. This, unfortunately, made the instrument somewhat cumbersome to use. The pumped helium system and the small ADR limited the experimental time to about 12 hours per cycle, and required cryogen fills and pumpdowns at least every other day. Even with their deficiencies the XRS/EBIT instruments were in almost continuous use for over seven years. In contrast, the third generation instrument is a completely new instrument that was designed from the ground up to be a low maintenance permanent facility at the EBIT laboratory.

The EBIT Calorimeter Spectrometer (ECS) is the third generation calorimeter instrument at the EBIT facility [5]. It was completed and installed in November 2007 and has been running continuously for almost a year. The cryogenic system is completely new based on an atmospheric pressure (unpumped) liquid helium cryostat at 4.2K, a closed cycle $^3$He/$^4$He getter pumped refrigerator [6], and a single stage ADR. The ECS uses the $^3$He/$^4$He system, which has a base temperature of 340 mK, to cool the focal plane outer housing and to pre-cool the ADR. The ECS runs continuously for 65 hours at 50 mK before requiring a 3 hour recharge of the ADR and $^3$He/$^4$He system. Cryogens are filled every 2 weeks (liquid helium) and 3 days (liquid Nitrogen) and filling doesn't interfere with the operation of the spectrometer. Small improvements to the focal plane assembly improve the spectrometer performance to 4.5 eV FWHM at 6 keV for the 16 mid-band detectors as shown in Figure 2. The ECS detector array also includes 14 high-energy detector pixels that use 100 μm HgTe absorbers to increase the quantum efficiency at 60 keV to 32%. The spectral resolution of the high-energy detectors is also substantially improved to 32 eV at 60 keV. The ECS dramatically increases the efficiency of operating the calorimeter instrument at the EBIT facility, adds a substantial capability at high energies, and improves the gain stability and spectral resolution of the mid-band detectors. The fourth generation instrument, currently under construction, uses newer detector technology to, again, substantially improve the spectral performance across the entire band from 0.1 to 200 keV.

## 3. The Next generation EBIT calorimeter instrument

We are currently designing and constructing the next generation EBIT calorimeter instrument based on significant improvements in calorimeter technology developed for the Constellation-X (now the International X-ray Observatory) program. These detectors use superconducting transition edge thermometers and lithographically patterned x-ray absorbers to substantially improve the performance of the detector system. In addition, these detectors are readout using superconducting quantum interference device (SQUID) amplifiers that can be multiplexed to dramatically increase the pixel count of the instrument. The fourth generation instrument, termed the Transition Edge Microcalorimeter Spectrometer (TEMS), will use the same cryogenic package as the ECS described above but in a cryogen free pulse-tube dewar that will require no servicing. The prototype of this system is currently operating in our laboratory and runs for over 100 hours at 50 mK before an automatic 2.5 hour recycle is required. As shown in Table 1, the array scale, detector time constant, and spectral resolution are substantially improved over the ECS. The large simultaneous bandpass, efficiency, and spectral performance of the TEMS instrument will substantially increase the capability of our laboratory astrophysics program.

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