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The EBIT Calorimeter Spectrometer: a new, permanent user facility at the LLNL EBIT

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The EBIT Calorimeter Spectrometer (ECS) is currently being completed and will be installed at the EBIT facility at the Lawrence Livermore National Laboratory in October 2007. The ECS will replace the smaller XRS/EBIT microcalorimeter spectrometer that has been in almost continuous operation since 2000. The XRS/EBIT was based on a spare laboratory cryostat and an engineering model detector system from the Suzaku/XRS observatory program. The new ECS spectrometer was built to be a low maintenance, high performance implanted silicon microcalorimeter spectrometer with 4 eV resolution at 6 keV, 32 detector channels, 10 μs event timing, and capable of uninterrupted acquisition sessions of over 60 hours at 50 mK. The XRS/EBIT program has been very successful, producing many results on topics such as laboratory astrophysics, atomic physics, nuclear physics, and calibration of the spectrometers for the National Ignition Facility. The ECS spectrometer will continue this work into the future with improved spectral resolution, integration times, and ease-of-use. We designed the ECS instrument with TES detectors in mind by using the same highly successful magnetic shielding as our laboratory TES cryostats. This design will lead to a future TES instrument at the LLNL EBIT. Here we discuss the legacy of the XRS/EBIT program, the performance of the new ECS spectrometer, and plans for a future TES instrument.
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1. INTRODUCTION

In the summer of 2000, we installed a new cryogenic x-ray microcalorimeter spectrometer at the Electron Beam Ion Trap (EBIT) facility at the Lawrence Livermore National Laboratory (LLNL). The EBIT facility with collaborators at Columbia, Stanford, NASA/GSFC, and the Lawrence Berkeley Laboratory has a long-standing program to use the EBIT for measurements in laboratory astrophysics. The addition of our microcalorimeter instrument, the XRS/EBIT brought a critical new diagnostic to the laboratory astrophysics program as discussed below.

The Electron Beam Ion Trap is a unique instrument for studying hot astrophysical plasmas in the laboratory. The EBIT instrument at LLNL can produce virtually any ionization state of almost any element[1]. This includes all of the abundant astrophysical elements H through Ni. Using the EBIT we can construct monoenergetic and thermal distributions of electrons in collisional equilibrium with well-defined ionization states. Measurements of line energies, absolute cross sections, satellite lines, recombination rates, and charge exchange recombination emission has allowed us to carefully benchmark the atomic codes that form the basis of spectral fitting models in high-energy astrophysics. This has been particularly important in disentangling the complex L shell emission from Fe that contributes significantly to many observations performed with the high-resolution x-ray spectrometers on the *Chandra* and *XMM/Newton* observatories.

Our XRS/EBIT instrument[2] is a broadband, high-throughput, microcalorimeter x-ray spectrometer. The large band-pass of the instrument [0.1-100 keV] allows the simultaneous measurement of the direct excitation emission spectrum and the much weaker radiative recombination lines that are used to derive the absolute cross sections for specific atomic transitions. For example, we have recently completed measuring the absolute cross sections for all strong transitions in Fe XVII – Fe XXIII using the XRS/EBIT[3,4]. Further the non-dispersive nature of the spectrometer has allowed us to make the first high spectral resolution observations of charge exchange in astrophysical elements[5]. The end result of seven years of operation of this instrument is a strong record of scientific achievement and an excellent example of a mature, operational, low temperature detector system.

The XRS/EBIT was assembled quickly in the spring of 2000 and was never intended to be a permanent instrument. We are currently completing the successor instrument, the EBIT Calorimeter Spectrometer (ECS) that will be an easy to use facility instrument at the LLNL EBIT. Below we discuss the construction and performance of the XRS/EBIT and its successor instrument the ECS. In addition we briefly describe our proposed follow-on to the ECS instrument that will be based on Transition Edge Sensor (TES) microcalorimeters that we are developing for the *Constellation-X* observatory. These two follow on instruments will allow our laboratory astrophysics program to perform the critical measurements needed to interpret the results from the next generation of x-ray observatories including *Constellation-X, NeXT, XEUS,* and *Spectrum X-Gamma*

2. THE XRS/EBIT INSTRUMENT

The XRS/EBIT instrument was first deployed at the LLNL EBIT facility in July of 2000. The instrument is based on an engineering model detector system and microcalorimeter detectors from both our Astro-E/XRS and Suzaku/XRS programs. Each microcalorimeter uses an implanted Si thermistor fabricated in situ on a silicon-on-insulator (SOI) island that is then supported by four micro-machined silicon beams. The x-ray absorbers are fabricated from epitaxially grown HgTe that are then attached to each microcalorimeter using Stycast 1266 and microfabricated polymer tubes. Complete details can be found in Stahle et al[6]. The currently operating XRS/EBIT detector array is shown in figure 1.

The engineering model detector assembly[7] is a high fidelity prototype of the flight detector assembly. It has 32 detector channels divided into two groups of 16 that are operated independently. Each detector channel in the assembly is composed of a 90 Mohm load resistor, a junction field effect transistor (JFET) source follower operating at 130 K, and a common bias divider. The detector assembly also provides the thermal anchoring to the adiabatic demagnetization refrigerator (ADR) that cools the detector array to 60 mK, and the thermal isolation from the 1.5 K pumped helium tank. The detector array itself is housed within an inner detector box that is independently suspended from the outer 1.5K detector assembly using tensioned Kevlar yarn.

The XRS detector assembly is used without modification in a small laboratory cryostat. The detector assembly requires three thermal interfaces to operate: a 60 mK interface to cool the detector array with a heat load of ~250 nW, a 1.5 K interface to cool the outer detector housing with a heat load of ~100 μW, and a <20K heat sink to cool the heat intercepts from the JFET assemblies with a heat load of ~15 mW. In the XRS/EBIT instrument the entire 14 liter liquid helium tank is pumped to 1.5 K to supply the 1.5K and < 20K interface. The 60mK interface is supplied by a single stage ADR using a 50g ferric ammonium alum (FAA) salt pill and an automated mechanical heat switch. The ADR cycle is completely automated in software and takes about 45 minutes.

The performance of the XRS/EBIT is very good. The current detector array is from the same wafer as the flight Suzaku/XRS flight detector, yielding almost identical performance with 5.5-6.0 eV FWHM energy resolution at 6 keV. The ADR has a 12 hour hold time at 60 mK, and the liquid helium bath holds for about 36 hours pumped to 1.5 K when operated horizontally. Liquid nitrogen transfers are required daily.

3. THE EBIT CALORIMETER SPECTROMETER (ECS)

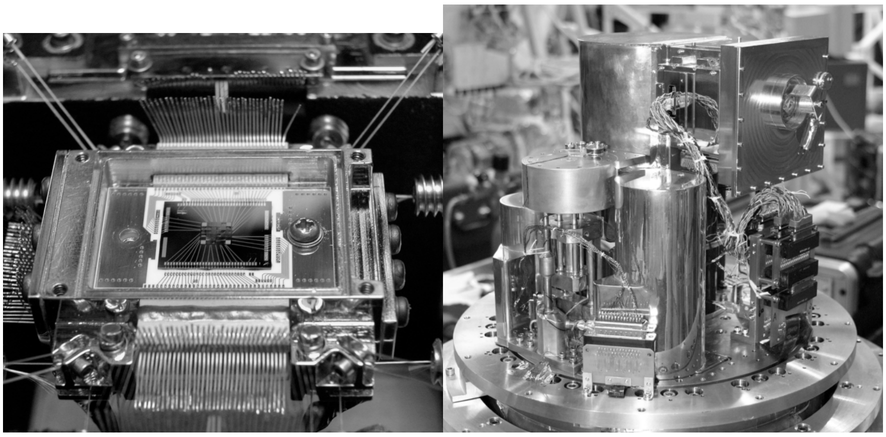

Fig. 1. (left) the XRS/EBIT detector stage with the 6x6 microcalorimeter array in the center. (right) the ECS cryogenics package with the He-3/He-4 sorption cooler in the foreground and the detector assembly at the top right.

The ECS instrument is designed to bring an easy to use, facility class microcalorimeter spectrometer to the EBIT facility. The XRS/EBIT, while performing very well for over seven years, is not trivial to use. It requires daily cryogen transfers, operates on large volumes of sub-atmospheric liquid helium, and the ADR cycle lasts for only 12 hours at 60 mK. In addition, we have made several advances in assembling and operating the XRS detector arrays to improve the performance of the instrument that we have incorporated into the ECS.

The final refrigeration and detector assembly is shown in figure 1. The entire cryogenic assembly requires only a 4 K interface that can be provided by either a mechanical cooler or a liquid helium volume. No external plumbing is required. A completely self-contained He-3/He-4 sorption cooled refrigerator from Chase Cryogenics[8] cools the outer detector assembly to 340 mK with a 15 J cooling capacity. The sorption cooler uses two internal pressurized helium tanks that also act as sorption pumps to provide refrigeration. In operation, He-4 is condensed using the 4K interface and is then used to condense the He-3. The ADR is composed of a 100 g FAA salt pill that is attached to the sorption cooler using a passive gas-gap heat switch. Both the ADR and the sorption cooler are cycled simultaneously under software control with the heat of magnetization dumped to the He-4 sorption cooler at 820 mK. Once the He-4 is exhausted, the ADR is demagnetized and the He-3 side of the sorption cooler is activated to cool the outer detector housing and the ADR suspension to 340 mK for the duration of the cycle. The ADR/sorption cooler cycle is completely automated and requires about 2 hours. The cryogenic assembly in the ECS spectrometer is attached to a 32 liter liquid helium dewar that is guarded by 25 liters of liquid nitrogen.

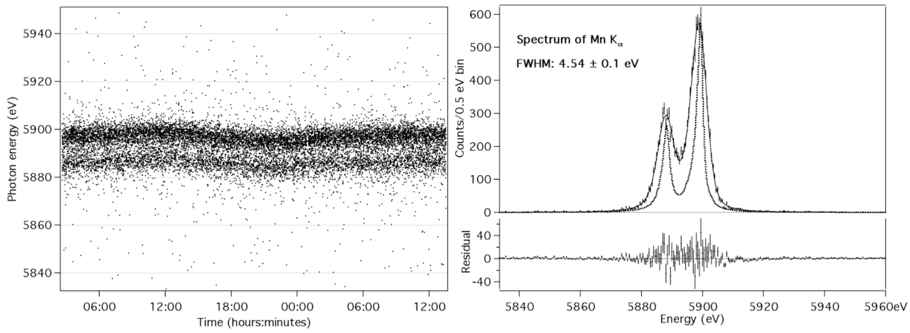

Fig. 2. (left) photon energy vs. time and (right) an energy spectrum for a 36 hour observation of a ^{55}Fe source. The gain stability over 36 hours was better than 3 eV (left) and the energy resolution, as fit, (right) was 4.5 eV FWHM at 6 keV for a 625x625x8 μm absorber.

The performance of the ECS is excellent. The ADR/sorption cooler has a hold time of over 60 hours at 50 mK with the detector assembly operating and is only limited by the capacity of the He-3 cooler. The ADR can easily be operated at under 40 mK without limiting the hold time. The temperature stability of the detector stage was very good at <100 nK rms at 50 mK. The liquid helium hold time is 18 days at atmospheric pressure and the liquid nitrogen hold time is 7 days. Thus the ECS cryogenic system is very easy to operate, requiring only infrequent cryogenic servicing that does not disturb the operation of the refrigerator.

We also made several important modifications to the detectors and detector assembly. A new detector assembly was fabricated for the ECS. The load resistors in the detector assembly were increased from 90 MOhms to 120 MOhms to increase stability at low temperatures, and, as in the flight system, control thermometry was added directly to the detector stage. In addition, infrared absorbing material was added to the inside of the detector box to minimize any stray power absorbed by the detectors.

Using the same test array that gave 3.2 eV FWHM resolution at 6 keV for a 400x400x8μm absorber and 3.7 eV for a 625x625x8μm absorber[9] in our laboratory system with 180 MOhm load resistors, we achieved 3.6 eV and 4.5 eV respectively in the ECS. The spectrometer is, also very stable. Figure 2 shows the photon energy vs. time for a 36 hour data set that yields a 3 eV day/night oscillation and no other gain drift structure. The spectrum of the data is also shown.

We are currently preparing the final detector array for the ECS spectrometer that will consist of 16 625x625x8 μm HgTe absorbers with a predicted resolution of 4 eV at 6keV and 16 625x625x100 μm HgTe absorbers with a predicted resolution of 22 eV at 60 keV[10]. Final delivery of the ECS spectrometer is expected in October 2007.

4. SUMMARY AND A FUTURE TES INSTRUMENT AT EBIT

The XRS/EBIT spectrometer has been producing science results for over 7 years and the ECS spectrometer will enhance this program by extending the band-pass to over 100 keV with high efficiency, improved energy resolution, and a much easier to use instrument. However, to provide the tools necessary to analyze the observations of the next generation of x-ray observatories we will require similar performance in the laboratory as will be available in space. Thus we have proposed to leverage our detector development program for the *Constellation-X* observatory to provide the same level of performance in a robust laboratory instrument. Specifically we have proposed to construct a microcalorimeter instrument based on time division multiplexed TES microcalorimeters using the same cryogenics package as the ECS instrument described above but integrated into a cryogen-free cryostat. The proposed spectrometer would have a 16x16 monolithic hybrid array consisting of 128 low-band pixels with 0.8 eV resolution from 0.1-1.5 keV and 128 mid-band pixels with 2.0 eV FWHM resolution from 0.1-10 keV. In addition, the instrument would have a second 8x8 array of high-energy detectors with 1mm x 1mm x 250 μm Sn absorbers with an energy resolution below 30 eV at 60 keV.

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