Time-of-Flight Detector System of the IBEX-Lo Sensor with Low Background Performance for Heliospheric ENA Detection

E MÖBIUS[1], S FUSELIER[2], M GRANOFF[1], E HERTZBERG[2], B KING[1], H KUCHAREK[1], S LIVI[4], S LONGWORTH[1], N PASCHALIDIS[5], L SAUL[3], J SCHEER[3], C SCHLEMM[5], M WIESER[6], AND P WURZ[3]
[1]*Space Science Center, University of New Hampshire, Durham, NH 03824, U.S.A.*
[2]*Lockheed Martin Advanced Technology Center, Palo Alto, CA, U.S.A.*
[3]*Physikalisches Institut, Universität Bern, Bern, Switzerland*
[4]*Southwest Research Institute, San Antonio, TX, U.S.A.*
[5]*Applied Physics Laboratory, Laurel, MD, U.S.A.*
[6]*Swedish Institute of Space Physics, Kiruna, Sweden*
eberhard.moebius@unh.edu

Abstract: IBEX-Lo on the Interstellar Boundary Explorer (IBEX) will map energetic neutral H atoms (ENA) from the termination shock at energies of 10 – 2000 eV and also image the interstellar O flow in spring and fall. The sensor combines a mechanical collimator to restrict the detectable arrival directions, an atom to negative ion conversion surface, an electrostatic analyzer, post-acceleration up to 20 keV, and time-of-flight (TOF) analysis, providing species separation and effective background suppression. Because the flux of the heliospheric ENAs is very low a triple coincidence system has been fabricated, tested, and calibrated for IBEX-Lo This system uses secondary electrons produced at two consecutive carbon foils, followed by detection of the ions in a micro-channelplate. These signals are combined into three independent TOF measurements. The combination of several TOF measurements is very effective at suppressing background to unprecedented levels. This scheme allows identification of minor species, whose fluxes are several orders of magnitude below the main species. Results from the testing of both the engineering and the flight unit will be discussed in the light of the IBEX science objectives.

Introduction

The scientific objective of the Interstellar Boundary Explorer (IBEX) mission is to explore the global interaction of the local interstellar cloud (LIC) with the heliosphere. This objective is achieved by imaging the sky in energetic neutral atoms (ENA) in the energy range 10 – 6000 eV [1]. Within the heliosphere there are two major heliospheric sources of ENAs. The first is the interstellar wind (i.e. the flow of interstellar neutral atoms through the solar system generated by its journey relative to the LIC). The physical parameters of the LIC and aspects of its interaction with the heliosphere can be derived from study of this source (e.g. [2]; [3]). The second source are the ENAs that are generated through charge exchange in the interstellar gas flow from the ion distributions that are slowed down, heated, and accelerated at the heliospheric termination shock. These ENAs constitute a diffuse particle source that carries information about the nature of termination shock and the interactions of ions with the shock ([4]; [5]).
Making use of this information, IBEX will pursue four fundamental questions: I. What is the global strength and structure of the termination shock? II. How are energetic protons accelerated at the termination shock? III. What are the global properties of the solar wind flow beyond the termination shock and in the heliotail? and IV. How does the interstellar flow interact with the heliosphere beyond the heliopause? The first three questions are answered by exploiting the diffuse source of ENAs, i.e. H atoms from the termination shock and downstream in the heliosheath. The fourth question is answered by observing the angular

distribution of the interstellar O flow at 1 AU. According to plan IBEX will be launched in June 2008, when it will join the current heliospheric fleet of spacecraft that provides in-situ and remote sensing observations from the Sun to the heliosheath.

Description of the Sensor

IBEX observations will be made with two large geometric factor single-pixel ENA cameras that cover the energy range with a comfortable overlap on a Sun-pointing spinning spacecraft in a high elliptical orbit. IBEX-Hi covers the energy range of 250 – 6000 eV and IBEX-Lo 10 – 2000 eV. The key requirements for both cameras are large collecting power and excellent suppression of any unwanted background in order to unambiguously detect the low fluxes of the termination shock ENAs of $5\cdot10^{3}$ – $1.5\cdot10^{5}$ cm^{-2} s^{-1} sr^{-1} in the energy range from 200 eV to 10 keV [5]. Simultaneously the sensors must provide an angular resolution of ≤ 7° FWHM (with a high-resolution section for IBEX-Lo of 3.5°). To achieve this, both sensors combine a large entrance aperture collimator with consecutive electron and ion rejection, conversion of the incoming neutrals into ions (positive for Hi and negative for Lo), energy selection in an electrostatic analyzer, and detection in a triple coincidence detector system. In addition, IBEX-Lo has the capability to distinguish the ions by mass through post-acceleration by nominally 16 kV (maximum 20 kV) and subsequent triple time-of-flight (TOF) analysis. In this paper we restrict our discussion to the IBEX-Lo sensor. In particular, we emphasize the novel triple TOF subsystem, which simultaneously provides mass discrimination and excellent background suppression. To our knowledge a nested triple TOF system is being used for the first time in a space application.
The TOF unit has been adapted from the Cluster CODIF sensor and its successors ([6]; [7]). Because of the extreme importance of background suppression for the IBEX mission, two similar TOF sections have been nested in order to achieve a genuine triple coincidence for the incoming ions. Figure 1 shows a schematic radial cut of the TOF subsystem together with the major electronic blocks. The incoming ions generate secondary electrons at the first carbon-foil that are guided to the outermost section of the micro-channel plate (MCP) detector. Similarly, electrons are generated at the second foil and guided to the innermost section of the MCP. The ions are detected in the center section, which is divided into 4 quadrants to allow for a separate background characterization. A single MCP pair is used. The anode pattern that provides for these signals is shown in the upper right of Fig. 1. Three TOF values are determined between each of the foils and the MCP (TOF0 and TOF1) and between the two foils (TOF2). Each of these three TOF measurements is equivalent to the observation with a CODIF-like sensor. The ability to use any of the three measurements provides for very high efficiency. The quadrant position is derived from a delay line TOF measurement (TOF3). Ion detection with a maximum of background suppression is achieved when all 4 TOF signals are registered.

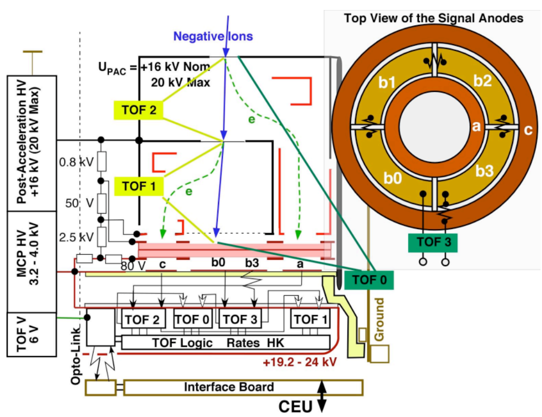

Figure 1: Functional schematics of the IBEX-lo TOF system. A radial cut is shown on the left with a blockdiagram of the main electronic elements. A top view of the signal anodes is shown on the right with the 4 quadrant anodes in the Stop portion of the MCP, which are connected by delay lines. All 4 TOF measurements are indicated.

IBEX-Lo Test Results

For IBEX-Lo an engineering test unit of the TOF subsystem and a flight unit have been designed and built, which have been thoroughly tested and calibrated with positive and negative ion beams. These tests demonstrate that the TOF unit meets

ICRC 2007 Proceedings - Pre-Conference Edition

the expectations in mass resolution and exceeds them as far as background suppression and efficiency are concerned.

Figure 2 shows a series of TOF2 (H1, H2) and TOF0 (H3, H4) histograms and TOF1 vs. TOF0 scatter plots (S1 – S4) from an H atom beam test with post-acceleration HV at 16 kV for 0 - 160 ns (a range including ions up to the mass of O). S1 shows all events that contain at least one of the three TOF measurements. Likewise, the left histogram for TOF2 and TOF0 (H1 and H3) contain all events flagged valid for the respective TOF measurement. Except for an easily identifiable peak at 0 ns in TOF2 and two very small "ghosts" (also seen in S1) near 0 ns in TOF0 the single TOF histograms provide already a clean H distribution. Note, that during background measurements each of the three double coincidence rates, taken with a minimum TOF threshold of 10 ns, is lower than 10^{-3} s^{-1}.

S2 only contains events with all three TOF and the delay line measurement. In addition, a condition is employed for the checksum of all TOF measurements: $|TOF0 + TOF3 – TOF1 – TOF2| <$ 1ns. Because of the way the start and stop signals are combined this sum contains only electronic propagation differences. Its distribution shows a FWHM of <0.6 ns, indicating that the electronic TOF resolution of each channel is better than 0.3 ns. All events with TOF = 0 in one of the channels are eliminated along with a number of events that fall outside the H distribution, which still shows two distinct peaks (from S1 related to the two peaks in the histogram H3 by arrows) due to the contribution of signals from two quadrants with different delay times. In S3 and S4 this is corrected by plotting TOF0+TOF3/2 and TOF1-TOF3/2, thereby consolidating the H distribution. H2 and H4 show histograms of only clean triple coincidence events after the delay correction. Finally, in S4 the events have been constrained to the H peak to the 1% level, as identified with TOF2 in histogram H2, thus seeking consistency between all three TOFs. Only events within the H box remain and a few along two diagonal lines with slopes of 1 and 0.5 in TOF0 vs. TOF1 (two dashed lines in S4), as is expected for stronger energy straggling in the second or first foil, respectively. There is a residual <0.5% peak from cross-talk to the delay line anode on the slope 1 line, indicating that it also contains legitimate H events. Note, that during an extensive background run over 2.5 days no H count was found with triple coincidence, thus exceeding even our ambitious goal of less than 1 count per day.

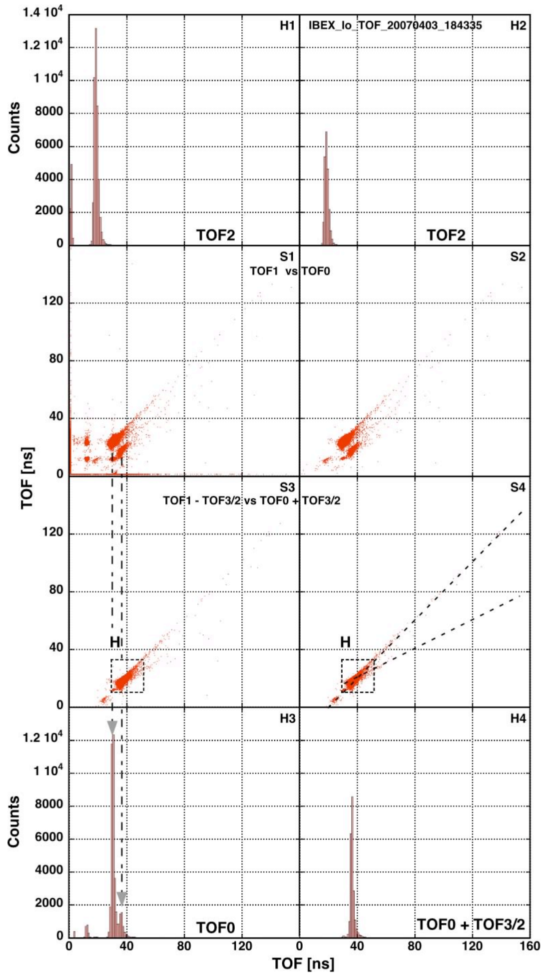

Figure 2: Sequence of TOF2 histograms H1 and H2, TOF1 versus TOF0 scatter plots that shows the successive removal of background and ghost signals from S1 through S4, and TOF0 histograms H3 and H4, as described in the text.

In spite of its emphasis on excellent background suppression, the IBEX-Lo TOF subsystem also provides high detection efficiency, which is very homogenous over the entire unit. For highest background suppression triple coincidence is used, and for highest counting statistics any single TOF measurement is accepted. Both efficiencies have been derived from calibrations with neutral beams for the nominal post-acceleration voltage

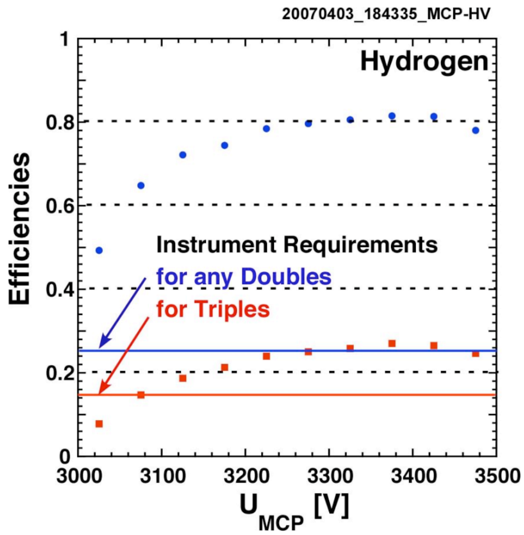

Figure 3: Triple (red) and double (blue) coincidence TOF efficiencies for H as a function of MCP + electron acceleration voltage in comparison with the instrument requirements.

of 16 kV. Because of the triple TOF measurement the detection efficiency of each of the two Start (a and c) anodes and the four Stop quadrants (delay line b0 and b3), can be determined directly with the TOF unit without any knowledge of the absolute beam flux, simply as the ratio of the triple coincidence rate and any of the three TOF (0, 1, and 2) rates. For example, the efficiency of Start a is the ratio of the rate of all valid triples and the rate for TOF1. The efficiencies for triple and any double coincidence as a function of MCP voltage for H are shown in Fig. 3. Both detection efficiencies reach a plateau above ≈ 3200 V combined MCP and electron acceleration voltage. At plateau level the triple coincidence efficiency reaches 27% and the combined double efficiency for all three TOF measurements 82%. Both values exceed the requirements of ≥15% (red line) and ≥25% (blue line) as well as the goals of ≥25% and ≥35%. To calculate the effective geometric factor of the TOF unit the transmission of the two foil support grids (80% each) has to be taken into account. This leads to overall transmission and detection efficiencies of 17.3% and 52.5%, respectively, which are remarkably high for a nested TOF unit. These efficiency values are found almost homogeneously around the entire cylindrical TOF unit, with only narrow shadows at radial spokes for structural support.

Conclusions

The IBEX-Lo Time-of-Flight unit unambiguously separates H, He, and O and also can distinguish the contribution of C. It detects ions with high efficiency and suppresses noise, background, and cross-talk with extremely high suppression factors. At this point the flight unit has successfully passed environmental testing and calibration and is ready for launch in June 2008.

Acknowledgments: This work is supported by the NASA Explorers Program, the Swiss National Science Foundation, and PRODEX.

References

[1] D. McComas, et al., The Interstellar Boundary Explorer (IBEX), *Third IGPP Conference Proceedings* **679**, 834, 2004.

[2] H.J. Fahr, The extraterrestrial UV-background and the nearby insterstellar medium, *Space Sci. Rev.* **15**, 483-540, 1974.

[3] E. Möbius, et al., Synopsis of the Interstellar He Parameters from Combined Neutral Gas, Pickup Ion and UV Scattering Observations and Related Consequences, *Astron. Astrophys.* **426**, 897, 2004.

[4] M. Gruntman, E.C. Roelof, D.G. Mitchell, H.J. Fahr, H.O. Funsten, and D.J. McComas, Energetic neutral atom imaging of the heliospheric boundary region, *J. Geophys. Res.*, **106**, 15767–15782, 2001.

[5] P. Wurz, A. Galli, S. Barabash, and A. Grigoriev, Energetic Neutral Atoms from the Heliosheath, *AIP Conf. Proc.* **858**, 269-275, 2006.

[6] E. Möbius, et al., The 3-D Plasma Distribution Function Analyzers With Time-of-Flight Mass Discrimination for CLUSTER, FAST and Equator-S, Measurement Techniques in Space Plasmas, R. Pfaff, J. Borowski, D. Young eds., *Geophys. Monograph* **102**, 243, 1998.

[7] H. Rème, et al., The CLUSTER Ion Spectrometry Experiment, *Space Sci. Rev.* **79**, 303 - 350, 1997.