41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
10-13 July 2005, Tucson, Arizona

AIAA 2005-4265

Colloid Micro-Newton Thruster Development for the ST7-DRS and LISA Missions

John K. Ziemer* and Manuel Gamero-Castaño
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

and

Vlad Hruby†, Doug Spence, Nate Demmons, Ryan McCormick, Tom Roy
Busek Co., Natick, MA 01760

We present recent progress and development of the Busek Colloid Micro-Newton Thruster (CMNT) for the Space Technology 7 Disturbance Reduction System (ST7-DRS) and Laser Interferometer Space Antenna (LISA) Missions. ST7-DRS is a NASA New Millennium Program technology demonstration mission and part of the ESA LISA Pathfinder Mission. The LISA Mission is a joint NASA/ESA mission scheduled to launch in the next decade. These drag-free missions require precision microthrusters to provide low-noise spacecraft position control within approximately 10 nm of free-floating proof masses, used to detect gravitational waves. Both missions have similar microthruster performance requirements: a thrust range of 5-30 μN, a thrust resolution <0.1 μN, and thrust noise <0.1 μN $Hz^{-1/2}$ over the ST7-DRS and LISA measurement bandwidths. Although other microthrust propulsion systems are currently under development for the purpose at ESA, this paper focuses on the NASA microthruster technology development of the Busek Colloid Micro-Newton Thruster.

I. Introduction

The primary objective of the Laser Interferometer Space Antenna (LISA) is to detect and measure as yet unobserved gravitational waves produced by compact binary systems and mergers of supermassive black holes‡. Only interplanetary space can provide the relative disturbance free environment suitable for these long time scale (1-10,000 s) measurements that could lead us to a better understanding of the beginning and current state of the universe. Yet, even interplanetary space is subject to minute disturbances, such as solar wind, radiation, and photon pressure that could mask the influence of gravitational waves on free-floating proof masses. To shield the gravitational wave instrument, LISA consists of a precisely controlled set of spacecraft that follow the array proof masses within approximately 10 nm and provide a disturbance free environment. Calculations have shown that to reach the sensitivity level of interest, the disturbances to the proof masses can be no more than 3×10^{-15} m s^{-2} $Hz^{-1/2}$ in the 10^{-4}-1 Hz bandwidth[1].

To accomplish this challenging task and develop the technology that will make these measurements possible, the LISA Project is a jointly mission sponsored by the European Space Agency (ESA) and NASA. In addition, due to the unique and challenging nature of the measurements, each agency is sponsoring a technology demonstration mission prior to LISA in the near future. Space Technology 7 Disturbance Reduction System (ST7-DRS) is the US technology demonstration mission, sponsored through the NASA New Millennium Program and managed by the Jet Propulsion Laboratory (JPL)[2]. The LISA Test Package (LTP) is the European technology demonstration mission, part of the ESA LISA Program[3]. Both technology demonstration missions will be placed on the same spacecraft as part of the LISA Pathfinder Mission, scheduled to launch between 2008-2009. In the US, the LISA Project is managed by NASA Goddard Space Flight Center and will be operated by JPL. Once in orbit, the LISA Pathfinder

* Senior Engineer, Advanced Propulsion Technology Group, JPL M/S 125-109, Member AIAA.
† President, Busek Company, 11 Tech Circle, Natick, MA 01760, Member AIAA.
‡The LISA websites, http://lisa.jpl.nasa.gov/ and http://sci.esa.int/science-e/www/area/index.cfm?fareaid=27, provide the most comprehensive information and list of technical references available.

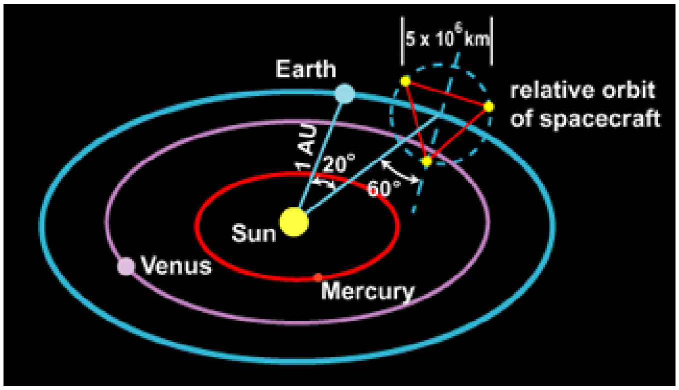

Figure 1. Orbit and spacecraft configuration for the LISA Mission. The constellation rotates as it orbits the sun.

Mission will last 6 months, while the baseline LISA mission is planned to last 5 years with the possibility of an additional 5-year extended mission. The ST7-DRS mission is currently in the implementation phase, and the LISA mission is currently in the planning phase.

Both NASA and ESA have parallel technology development programs, including plans to develop at least two microthruster technologies[4]. This paper describes only the US technology development effort in detail, focusing on the Busek Colloid Micro-Newton Thruster[5,6] (Refs. 7 and 8 provide information on the European technologies currently under consideration).

In this paper, we present a discussion of the microthruster requirements for both missions, the US technology development program for LISA, and the CMNT flight hardware development for ST7-DRS.

II. Microthruster Requirements

The LISA instrument consists of six proof masses, two in each of three Gravitational Reference Sensors (GRSs) that are on all three spacecraft, and a laser Interferometry Measurement System (IMS). Detection of gravitational waves follows from measuring the time-varying strain in the length between proof masses using a Michelson-type interferometer sensitive to picometer level displacements. As shown in Figure 1, the nominal arm length (the distance between spacecraft and reference proof masses) is 5 million kilometers with the spacecraft arranged in an equilateral triangle. The triangle formation is placed into a heliocentric orbit at 1 AU, 20 degrees behind the Earth by three propulsion modules that separate from each spacecraft after insertion. The plane of the triangle is tilted 60 degrees with respect to the ecliptic to maintain a stable orbit configuration. The Disturbance Reduction System (DRS) for each spacecraft consists of position sensors in the GRS, micronewton thrusters as actuators, and drag-free control laws that maintain the spacecraft orbits and cancel out the environmental disturbances (mainly solar photon pressure) to the spacecraft. The LISA Pathfinder Mission is a single spacecraft containing two complete DRSs, each with a GRS, IMS, and microthrusters as key components of the technology demonstration missions.

To observe gravitational waves effectively, the LISA instrument must operate in a drag-free environment with stringent, high-resolution requirements on both the pointing and the translation of the spacecraft. Since the stability of the spacecraft relates directly to the quality of the science measurements, the propulsion system is a critical component. Keeping the spacecraft centered on the proof masses requires thrusters capable of balancing the solar radiation pressure, including small variations. With three sets of two operational thrusters distributed equally around the spacecraft, thrust levels between 5-30 µN with a resolution of 0.1 µN and a thrust noise <0.1 µN/√Hz are necessary to meet these requirements. The microthruster requirements have been discussed in detail in Ref. 4 and are summarized here in Table 1.

Although ST7-DRS is the technology demonstration mission (mainly demonstrating performance), the full LISA mission has slightly different requirements, most critically a 25-time increase in lifetime. For LISA, the arrangement and number of thrusters reduces the average thrust demand per thruster head, requiring only 10 times the total impulse per thruster compared to the ST7-DRS mission. For LISA, the current baseline design has only sun-apposing thrusters, requiring the solar photon pressure for full control. Other LISA configurations (and the

Table 1. ST7-DRS and LISA Microthrust Propulsion Requirements.

Requirement	ST7 Value	LISA Value
Thrust Range	5 - 30 µN	4 - 30 µN
Thrust Precision	< 0.1 µN	< 0.1 µN
Thrust Noise	< 0.1 µN/ÃHz	< 0.1 µN/ÃHz
Operational Lifetime	2,200 hours	55,000 hours
Duration for Propellant Storage	3 months	8.5 years
Total Impulse	200 Ns for sun facing thrusters, 300 Ns for sun apposing thrusters	18,000 Ns over all thrusters, i.e. 3,000 Ns per thruster for six thrusters
Exhaust Contamination on Spacecraft	< 0.1 µg/cm2	TBD

ST7-DRS configuration) have more thruster heads including some in a sun-facing orientation to provide full control of the spacecraft without relaying on solar pressure. This leads to a higher average thrust as there is a steady bias in addition to the solar pressure. Maximum thrust for LISA is determined from tip-off and acquisition requirements but could be reduced in the future to the maximum thrust required for operations. This could be beneficial as the maximum and minimum thrust are determined by the number of emitters, and any reduction in the minimum thrust leads to a reduction in the average thrust demand, the total impulse and propellant mass requirement.

All of these requirements have not been demonstrated by any single microthruster technology to date, especially thruster lifetime, the most challenging requirement for LISA. Although thrust range, noise, and precision have been measured for the CMNT in the laboratory[9-11], the LISA requirement for 55,000 hours (5 years +25%) of operation with 8.5 years of expendable propellant has proven difficult to demonstrate. In fact, a lifetime of greater than 4000 hours has not yet been demonstrated by any of the thruster technologies being considered by either NASA or ESA. It is likely that the lifetime requirement will be met by models of thruster lifetime validated with shorter (3000-8000 hour) duration tests that will be critical to reducing the risk for the overall mission. Alternatively, excess noise from the thrusters and poor resolution would require a change to the control laws or possibly reduce the quality of the science data, but would not cause a loss of the mission. The other requirements should be not be difficult to meet given proper shielding and positioning of the thruster clusters, however a detailed study of the contamination issues is still warranted.

III. Microthruster Technology Development Plan

Currently NASA is responsible for developing solely US microthruster technologies, and ESA is responsible for solely developing European microthruster technologies for LISA. In the US, we are focusing on further development of the Busek CMNT to meet LISA requirements, specifically focusing on thruster lifetime issues. Thruster life will be determined by physics-based models validated by laboratory experiments and “short term” wear testing. This methodology must be employed because it impossible to demonstrate 55,000-hour lifetime by the end of the technology development program with ground tests alone. This requires multiple short duration (1000-4000 hr) tests to identify failure mechanisms and develop models of physics behind each failure mode. We will conduct one long duration lifetest (> 8000 hr) on a prototype thruster by the LISA Preliminary Design Review (PDR), currently scheduled for late 2009, to verify the models, perhaps continuing the test on through the Critical Design Review (CDR) if the project desires. A second priority will be measuring and understanding the properties of the exhaust beam including investigating contamination concerns.

As part of the recent activities for LISA, a detailed technology development plan for each critical sub-system has been submitted to NASA headquarters. ESA is currently preparing their own technology development plan, and the two will be consolidated in the next year. As part of the NASA technology development plan, over ten technology gates (including three microthruster gates) have been identified that must be completed before the LISA project PDR to demonstrate readiness to proceed into the implementation phase of the project. The three microthruster related technology gates include: microthruster performance, spacecraft interactions, and microthruster lifetime. Each gate, including the current status of the technology, will be described in detail below.

A. Technology Gate 1: Microthruster Performance

Passing this gate requires the microthruster technology to demonstrate, with direct measurements of thrust, thrust noise, and key thruster operating parameters (beam voltage, beam current, thruster head temperature), that the microthruster control algorithms are correct and that the system (including PPU and DCIU) can meet the mission DRS requirements:

- Thrust range from 4-30 μN
- Thrust precision of < 0.1 μN over full range of operation
- Thrust noise in the LISA bandwidth (0.1 mHz – 1 Hz) < 0.1 μN/√Hz

Component level validation (thruster head, micro-valve, electronics) is required for TRL 5 demonstration, and a system level demonstration is required for TRL 6. In the case that a testbed capable of measuring thrust noise within the complete LISA bandwidth or on-orbit measurements are not available, validated thrust models based on key thruster operating parameters and direct thrust measurements can be used to show compliance.

<u>Current Status:</u> The Busek Colloid Micro-Newton Thruster (CMNT) has completed this technology gate up to TRL 5, in terms of performance, at the component level. System level tests for ST7-DRS will be occurring within the next six months, after which, the CMNT could be classified as TRL 6 in terms of performance, although some validation of thrust noise at low frequencies must occur on orbit. The best available microthrust measurement testbed is only capable of measuring thrust noise < 0.1 μN/√Hz at and above 7 mHz. Below this value, validated

Figure 2. 2 m diam., 2 m long Ultra-high vacuum chamber at JPL showing Nano-Newton Thrust Stand inside chamber.

thrust models have been used to demonstrate meeting the thrust noise requirement for ST7-DRS, and it is likely the same approach will be used for LISA, although the performance testbeds could be improved if necessary.

B. Technology Gate 2: Spacecraft Interactions

Passing this gate requires the microthruster technology to demonstrate, with direct measurements and verified models of spacecraft interactions, that the operation of the microthruster will not interfere with normal spacecraft and science operations. This includes demonstrating that the exhaust plume of each thruster does not impinge on the spacecraft or interact with the local environment to contaminate the spacecraft surfaces in any way. This also includes demonstrating that the beam and spacecraft potential will not induce beam stalling or spacecraft charging during normal operation. Both of these items can be modeled and verified with measurements over the operational range of the thruster, some of which have already been conducted for ST7-DRS. This gate also includes the development and test of a cathode neutralizer providing the necessary electrons to neutralize the exhaust beam, although this is not expected to be a major technology development effort in the US.

Current Status: Models and measurements of the CMNT exhaust plume have shown that no charged particles exit the thruster beyond a 35-degree half-angle at the most divergent operating condition. Mass deposition measurements have shown that no measurable deposition occurs outside of a 45 degree half-angle, with more detailed measurements at various angles soon to follow. Plasma potential measurements show that beam potentials do not exceed +/- 50 V at any angle for a neutralized beam. Measurements of a non-neutralized beam have proven difficult due to facility effects and the low level of emission current; however, efforts are still underway to perform them. To date, all test show that the Busek CMNT should be able to meet LISA requirements once they are better defined. Still, testing should continue and be in place for the long duration tests to insure the plume characteristics (which can effect both performance and contamination) do not change over the thruster lifetime.

C. Technology Gate 3: Microthruster Lifetime

Passing this gate requires the development and validation of models including thruster wear and life-limiting mechanisms that can be used to demonstrate a 55000-hour lifetime (5 years of on-orbit operation with a 25% margin design guideline). Thruster wear and life-limiting mechanisms at the component level will be identified and modeled in a series of 3000-hour class tests performed by both the manufacturer and the LISA project. At least two system-level 3000-hour class tests will be used to investigate system-level failure mechanisms. During these tests, *in situ* diagnostics will be developed capable of providing data for model validation and to verify performance and spacecraft contamination requirements outlined above. Before PDR, the LISA breadboard system level thruster will be tested for at least 8000 hours without interruption to check the completeness and accuracy of the lifetime models and complete failure mode identification.

Current Status: Over seven 3000-hour class tests have been initiated at Busek to date. The first series identified and corrected a needle wear mechanism associated with the propellant electrochemistry and the needle material. During the test, Busek also identified a new potential concern of a gradual increase in the propellant feed pressure to supply the required propellant flow rate. Additional design changes were implemented and a new series of lifetests showed the problem was resolved for ST7-DRS lifetime (however, not necessarily for LISA lifetime). In 2005, Busek has a contract with the LISA project to investigate and model the electrochemistry near the emitter tips and other fundamental lifetime related issues. The first 3000-hour class test conducted by the LISA project will begin in early 2006.

D. Microthruster Testing Facilities at JPL

As shown in Figure 2, NASA, JPL, and the LISA Project have invested in a new facility, called the Microthrust Propulsion Laboratory, to study candidate microthrust propulsion systems for precision formation flying and drag-free missions. The laboratory opened in Sept. 2003 and is housed in a class 10 capable clean room with over 1000 sq. ft. of workspace for multiple projects. The laboratory contains a 2m diameter, 2m long Ultra High Vacuum (UHV) facility with automated operation and data acquisition systems for unattended operation. The UHV environment is absolutely necessary to test the integration of FEEP and Colloid thrusters with neutralizers and properly measure plume properties. The large size of the chamber will also reduce facility effects to unprecedented levels and allow for better contamination studies. The chamber is equipped with a Nano-Newton Thrust Stand, exhaust beam profiling and contamination diagnostics, and a load-lock system for rapid turn around or closer examination of the thruster head. Tests of the Busek CMNT for ST7-DRS and LISA have begun this year. The first 3000-hour class test is expected to begin next winter.

IV. Busek Colloid Micro-Newton Thruster

Colloid thrusters, currently under advanced development at Busek Co. Inc.[5,6], are a type of electrospray propulsion, as shown in Figure 3. A balance of surface tension and electrostatic forces create microscopic droplets (10 to 100 nm diam.) of a semi-conductive liquid (doped glycerol, formamide, tributyl phosphate, or ionic liquid, for example), which are extracted and accelerated by the same applied voltage. Multiple capillary tube needle arrays are generally required to produce greater than 1 µN of thrust effectively. Thrust can be throttled by changing the acceleration voltage and/or propellant flow rate. Unlike other electrospray thruster designs, colloid thrusters use an active propellant feed mechanism including a constant pressure propellant storage bellows and a precision microvalve that controls the flow of propellant to the emitter reservoir. Active control of the flow rate and the physical properties of the propellant (low vapor pressure) allow for two stages of electrodes: extraction and acceleration. The extraction voltage, V_E, is kept constant (~2 kV) to eliminate neutral production and provide a stable source of charged droplets. The acceleration or beam voltage, V_B, can be varied from 0-10 kV to provide variable thrust and specific impulse.

Heaters to liquefy the propellant are generally not required, but may be needed to stabilize the physical properties of the propellant and reduce low frequency thrust noise. In this case, heater power is generally <1 W. Colloid thruster performance is determined by the charge state of the droplets, the total beam voltage, the propellant flow rate, and the ion beam divergence. Typical performance ranges from 0.1-3 µN per emitter with a specific impulse between 500-1500 s and a thrust-to-power ratio of approximately 20 µN/W[10,11].

Out of all the electrospray microthrusters, the Busek Colloid Micro Newton Thruster (CMNT) is the most developed in terms of demonstrated performance, accumulating 3000 hours in a single needle full system test, and completing a critical design review (CDR) for the ST7-DRS Project in May of 2004. Figure 4 shows one breadboard thruster in a cluster configuration. In this figure one 6-needle thruster head and neutralizer are visible along with a full stack of 4 bellows for the quad-cluster. We will now discuss the subsystems of the Busek CMNT being developed for the ST7-DRS Mission that could also be useful for the LISA mission.

A. Thruster Head

The thruster head is comprised of a reservoir that feeds multiple capillary tube emitters and the electrodes that extract and accelerate the propellant. For the CMNT breadboard design, six emitters provided 1-20 µN with better than 0.1 µN resolution. As in previous designs, the thruster has both an extraction and an acceleration electrode allowing stable operation and variable thrust. Since the mass flow rate is controlled independently of the extraction voltage and the charge to mass ratio of the droplets depends on the mass flow rate, the thrust, T, is proportional to the total beam current, I, and voltage, V, $T \propto I^{1.5} \times V^{0.5}$. This relation shows the two methods of controlling the thrust. For small variations on time scales <100 ms, the accelerator voltage can be used to trim the thrust. For larger changes over longer times scales, the mass flow rate (hence the current) can be used to control the thrust. Reference 10 provides direct thrust measurements with varying voltage and current for the 6-emitter breadboard CMNT. Busek has also been able to measure thrust noise to sub-micronewton levels above

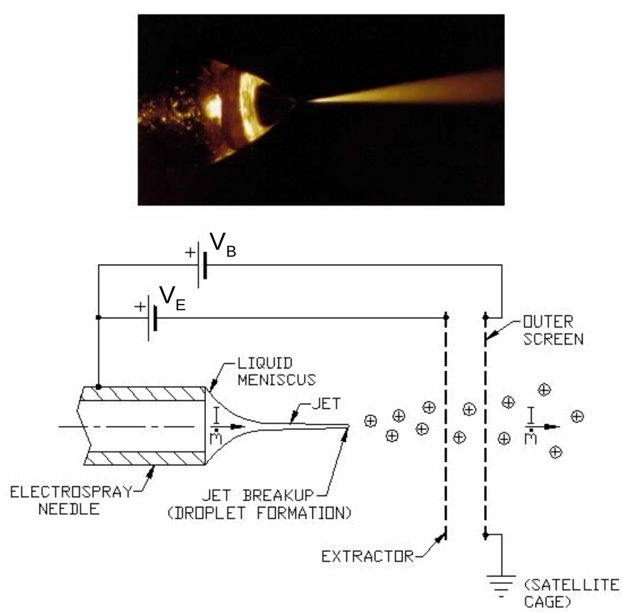

Figure 3. Colloid microthruster electrospray using tributyl phosphate (current propellant does not produce visible droplets) and a schematic of the thruster emitter. Taken from Ref. [11].

1 mHz[4,10]. Thrust measurements of a 9-needle emitter will be conducted at Busek in the next six months.

For LISA (and more recently for ST7-DRS) the thruster head will require at least 9 emitters to provide the range of 4-30 μN, although fewer emitters may be required if the maximum thrust level can be reduced. Since the remaining components will have a similar design, it is still expected that the thruster will have thrust noise and precision levels below 0.1 μN

B. Propellant Feed System

Ionic liquids are an attractive propellant for colloidal microthrusters because of their high conductivity and negligible vapor pressure. An ionic liquid is simply a salt that is liquid at or near room temperature. For ST7-DRS the ionic liquid has a melting temperature of –55°C and a boiling point of 240°C. The vapor pressure is believed to be lower than 10^{-12} Torr, although the exact value has proven difficult to measure. This attribute is important to enable larger diameter needles that increase the attainable thrust level per needle without the concern of evaporation, also an attractive quality in terms of spacecraft contamination. A high conductivity propellant, such as an ionic fluid, enables higher specific impulse operation and reduces the voltage drop through the cone-jet to improve thruster efficiency. Since precision and accuracy of the thrust is key to meet mission requirements, the stability of the physical properties of the propellant during operation and throughout the mission is very important.

Because of the organic backbone and high molecular weight nature of the propellant, there were concerns that the radiation environment during the mission could breakdown propellant molecules, change important physical characteristics of the liquid propellant, and produce precipitants and/or volatiles that may interfere with proper thruster operation. Radiation has been shown to influence colloid thruster performance previously in the 1970's when researchers used glycerol doped with sodium iodide for propellant that was shown to decompose under high-energy electron bombardment. However in tests at JPL, radiation to levels 10 times that expected for LISA did not measurably change thruster operation[12]. In those same tests in was also found that both the radiated and non-radiated samples did not evaporate significantly below 80° C.

Propellant is stored in a stainless steel bellows compressed by four constant force springs set to supply the microvalve (μValve) with approximately 1 atmosphere of pressure. Shown in Figure 5, the μValve is piezo-actuated using ~1 mW of power to control the propellant flow rate to better than 1 nA equivalent resolution. This level of precision corresponds to ≤0.01 μN of thrust, with a response time less than 0.5 s. The

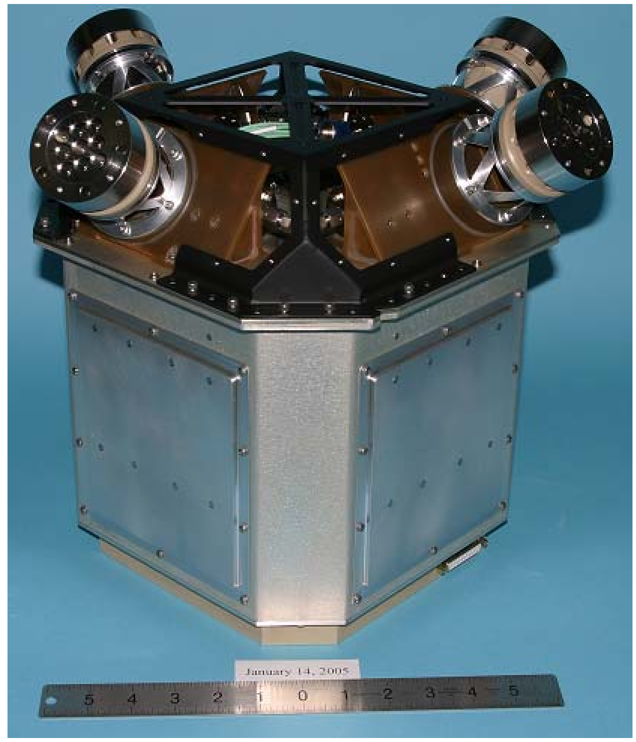

Figure 4. Breadboard Busek Colloid Micro Newton thruster showing one complete thruster (thruster head, neutralizer, PPU and propellant storage bellows unit) in a quad configuration. Taken from Ref. [5].

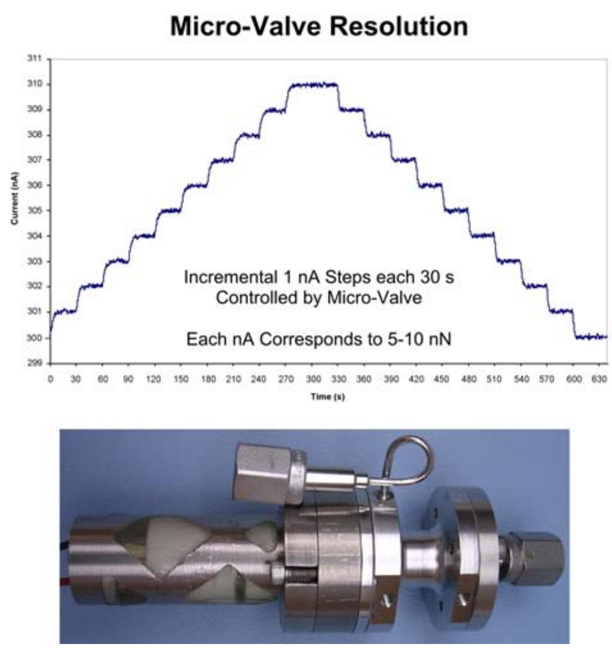

Figure 5. Busek CMNT Piezo-actuated Microvalve and graph of valve response shows < 0.1 μN resolution. Taken from Ref. [5].

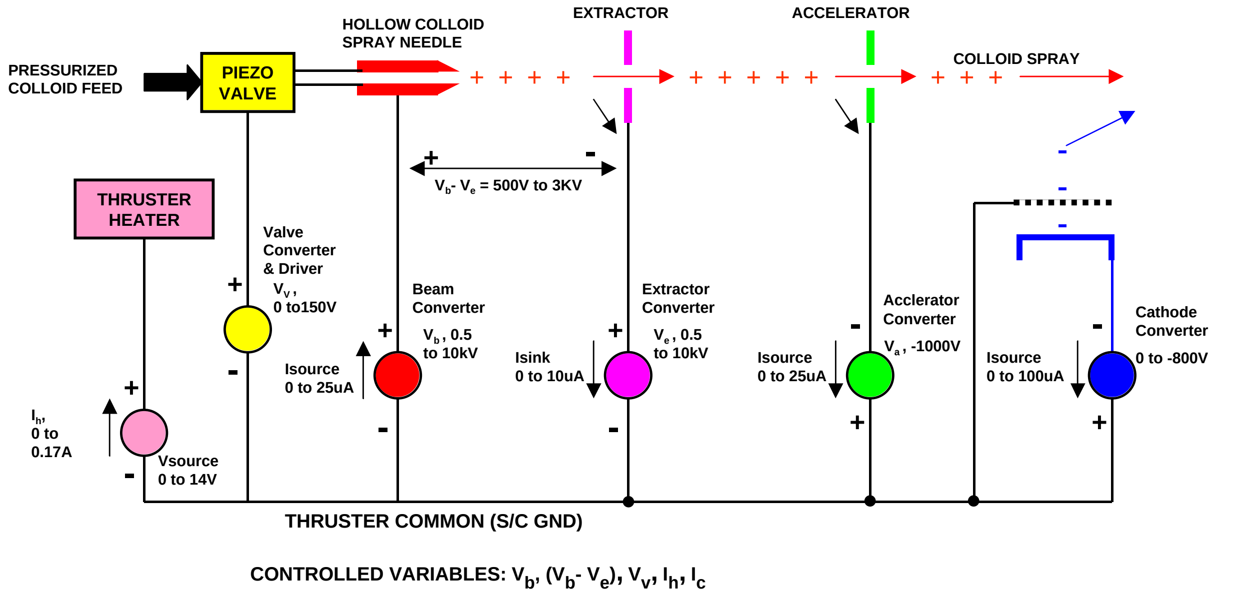

Figure 6. Thruster electrical schematic showing beam, emitter, extractor, accelerator, and cathode neutralizer voltage sources. Taken from Ref. [5].

microvalve has been part of multiple 3000 hour long-duration tests, performing without incident.

C. Cathode Neutralizer

The cathode neutralizer developed by Busek is made from a carbon nanotube (CNT) base with an extractor electrode. The cathode is capable of producing 10 μA to 1 mA using extraction voltages of 250-770 V. One CNT cathode has been tested in an ultra-high vacuum chamber for over 13000 hours at 100 μA without incident. For ST7-DRS, there will be one cathode neutralizer per thruster cluster, but only one neutralizer is required to prevent spacecraft charging, allowing for some redundancy. Interestingly, for ST7-DRS the neutralizer may not even be needed as the photo emission from the solar panels will likely be enough to neutralize all the colloid beams, about 30 μA maximum. This technology could also be used for the LISA Mission, and its development and testing will be included in the US microthruster technology development program.

D. Thruster Electronics

The thruster electronics including 4 power processing units (PPUs) and one digital control and interface unit (DCIU) for each cluster have been developed and tested to the breadboard level. The PPU also includes the high-voltage DC-DC converters that have been specifically designed and tested for this application by Busek Co. As schematic of the PPU is shown in Figure 6. Breadboard and engineering model level components are being used in long duration testing to demonstrate lifetime.

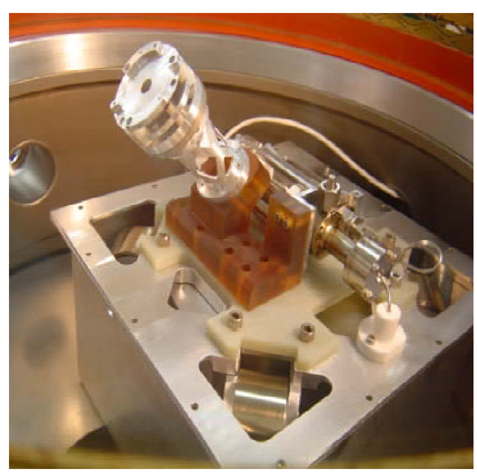

Figure 7. Single emitter colloid microthruster system in a 3000-hour lifetest. Taken from Ref. [5].

E. Thruster Lifetime Testing

Lifetime is the key requirement in the LISA technology development effort. Currently lifetime tests are focused at demonstrating the ST7-DRS requirement (2,200 hours minimum), but have also pointed out the prime lifetime concerns related to the electrochemistry at the tip of the emitter. Busek has conducted a number of long duration tests at both the component and system level. In the last year, two of the most important 3,300-hour class tests with a single needle emitter have been used to demonstrate how design changes in terms of materials, component sizes, layout, etc. can improve thruster lifetime. Both of the tests use a full thruster system in terms of the thruster head, micro-valve, and bellows propellant supply system (cathode neutralizer tests have been conducted separately showing greater than 13,000 hours of continuous operation.

In the first test, emitter erosion was examined as a function of time. Earlier tests had shown that some materials had incompatibilities with the ionic liquid propellant; however after 3635 hours, no degradation of the emitter tip was observed under SEM measurements and the test was stopped voluntarily. During this test, questions of the electrochemistry process near the emitter tip and at junctions between the various feed system components were raised as a new phenomenon was observed during the last 1000 hours of the test. During this period, the microvalve voltage was gradually increased to maintain a constant current. Although the valve voltage never exceeded the design limits, it was felt that the design margin could be improved. After slight modifications to the feed system, the thruster system again accumulated 3406 hours of continuous operation without incident. In this test, a very slight increase (1/10th the previous rate) in valve voltage was observed, although this can be attributed to a gradual decrease in daily average laboratory temperature by 8°C over five months. This second test demonstrated that a single emitter colloid thruster system could provide the ST7-DRS lifetime with enough operational margin. Currently Busek is preparing a full system 3000-hour class test with a 9-needle emitter system.

V. Conclusions

Under current plans, one or more microthruster technologies will be developed to the point of meeting the LISA requirements. The US technology development effort will focus on further developing the Busek CMNT to meet LISA specifications, specifically focusing on lifetime. Facilities have been developed to support long duration testing and beam profiling under ultra-high vacuum conditions. Over the next four years a series of 3000-hour class tests and one 8000 hour test will be used to verify models of thruster lifetime and help develop the thruster to a breadboard level for LISA. Research efforts at ESTEC and ESA will also continue in parallel, helping to insure that at least one technology is ready to use for LISA by the preliminary design review.

Acknowledgments

The authors would like to acknowledge the contributions of Stephen Merkowitz and Eric Cardiff from NASA Goddard Space Flight Center for their contribution to the technology development plan.

The research work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

[1]R.T. Stebbins, P.L. Bender, J. Hanson, C.D. Hoyle, B.L. Schumaker, and S. Vitale, "Current Error Estimates for LISA Spurious Accelerations," *Class. Quantum Grav.*, Volume 21, 2004, pp. S653-S660.

[2]W.M. Folkner, et al, "Disturbance Reduction System: Testing Technology for Precision Formation Control," *Proceedings of the SPIE*, Volume 4860, 2003, pp. 221-228.

[3]D. Bortoluzzi, et al, "Testing LISA Drag-Free Control with the LISA Technology Package Flight Experiment," *Class. Quantum Grav.*, Volume 20, 2003, pp. S89-S97.

[4]J.K. Ziemer and S.M Merkowitz, "Microthrust Propulsion for the LISA Mission," *40th AIAA Joint Propulsion Conference*, Fort Lauderdale, FL, 2004, AIAA-2004-3439.

[5]V. Hruby, et al, "Busek Colloid Thruster Development," *3rd Colloid Thruster Nano-Electrojet Workshop*, MIT, Boston, MA, April 14-15, 2005.

[6]V. Hruby, et al, "Colloid Thrusters for the New Millennium, ST7 DRS Mission", *IEEE Aerospace Conference*, Big Sky, MT, IEEEAC-1329, 2004.

[7]S. Marcuccio, A. Genovese, M. Andrenucci, "Experimental Performance of Field Emission Microthrusters", *J. Prop. Power*, Vol. 14, No. 5, September–October 1998.

[8]M. Tajmar, A. Genovese, and W. Steiger, "Indium Field Emission Electric Propulsion Microthruster Experimental Characterization", *J. Prop. Power*, Vol. 20, No. 2, March-April 2004.

[9]M. Gamero-Castaño, V. Hruby, D. Spence, N. Demmons, R. McCormick, C. Gasdaska, and P. Falkos, "Micro Newton Colloid Thruster for ST7-DRS Mission," *39th AIAA Joint Propulsion Conference*, Huntsville, AL, 2003, AIAA-2003-4543.

[10] M. Gamero-Castaño, "A Torsional Balance for the Characterization of Micro Newton Thrusters", Rev. Sci. Inst. 74 (10): 4509-4514, Oct. 2003.

[11] M. Gamero-Castaño and V. Hruby, "Electrospray as a Source of Nanoparticles for Efficient Colloid Thrusters," *J. Prop. Power*, Vol. 17, No. 5, September–October 2001.

[12] J.K. Ziemer, et al, "Colloid Thruster Propellant Stability after Radiation Exposure", *39th AIAA Joint Propulsion Conference*, Huntsville, AL, 2003, AIAA-2003-4853.