Microthrust Propulsion for the LISA Mission

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We present the most recent propulsion requirements for the Laser Interferometer Space Antenna (LISA) Mission and describe potential microthruster technology that can meet these requirements. LISA consists of three spacecraft in heliocentric orbits, forming a triangle with 5×10^6 km sides that are the arms of three Michelson-type interferometers. Reflective proof masses provide the reference surfaces at the end of the interferometer arms as part of the Gravitational Reference Sensor (GRS) designed to detect gravitational waves. The microthrust propulsion system will be part of the Disturbance Reduction System (DRS), which is responsible for maintaining each spacecraft position within approximately 10 nm around the proof masses. To provide the necessary sensitivity, the GRS must not experience spurious accelerations $>10^{-15}$ m s^{-2} $Hz^{-1/2}$ in the 0.1 mHz to 1 Hz bandwidth, requiring precision formation flying and drag-free operation of the LISA spacecraft. This leads to the following microthruster performance requirements: a thrust range of 2-30 μN, a thrust resolution <0.1 μN, and thrust noise <0.1 μN $Hz^{-1/2}$ over the LISA measurement bandwidth. The microthruster must provide this performance for 5 years continuously, contain 10 years worth of propellant, and not disrupt the science measurements. Potential microthruster technologies include Colloid, Field Emission Electric Propulsion (FEEP), and precision cold gas microthrusters. Each of these technologies is described in detail with focus on the NASA microthruster development of the Busek Colloid Micro-Newton Thruster (CMNT).

I. Introduction

The LISA Mission's primary objective 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 radiation, wind and photon pressure, that could mask the influence of gravitational waves on free-floating proof masses. To shield the instrument, a precisely controlled set of spacecraft must be made to follow the proof masses and provide a disturbance free environment. Calculations have shown that for 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, LISA is jointly sponsored by the European Space Agency (ESA) and NASA. LISA is currently in the pre-formulation phase and is scheduled to launch in 2012 following the LISA Pathfinder technology demonstration mission scheduled to launch in 2007. LISA is a Cornerstone mission in ESA's Cosmic Vision Programme and a Great Observatory in the Structure and Evolution of the Universe: Beyond Einstein Program, part of NASA's Astronomy and Astrophysics Division. In the US, the LISA Project is managed by NASA Goddard Space Flight

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‡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.

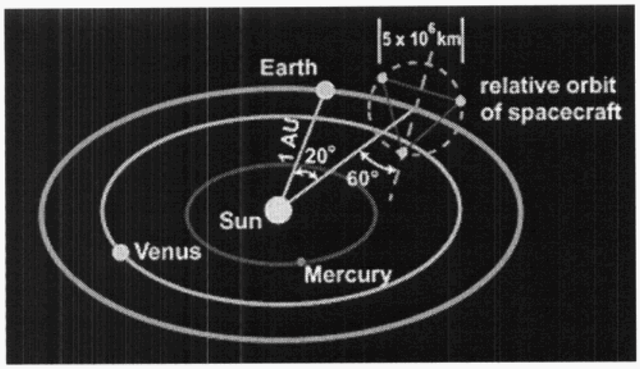

Figure 1. Orbit and spacecraft configuration for the LISA Mission. The constellation rotates as it orbits the sun.

Center and will be operated by the Jet Propulsion Laboratory. Once in orbit, the baseline mission is planned to last 5 years with the possibility of an additional 5-year extended mission.

The LISA instrument consists of six proof masses, two in each of three Gravitational Reference Sensors (GRSs), 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 (detailed in Ref. 2) 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. Since the coupling between the spacecraft and free-floating proof masses is required to be small, the maximum allowable disturbance on the spacecraft for effective drag-free operation is calculated[1] to be 3×10^{-10} m s^{-2} $Hz^{-1/2}$.

This paper focuses on the requirements and related technology development of the micronewton thrusters for the LISA DRS. Micronewton thruster technology is considered a key component for LISA and is currently being developed by both NASA and ESA, including space flight tests during their respective DRS technology demonstration missions. In the US, NASA's New Millennium Program has selected the Disturbance Reduction System (DRS) for the Space Technology 7 (ST7) technology demonstration mission[3]. In Europe, ESA is developing the LISA Technology Package (LTP) flight experiment[4] to test and demonstrate all the critical components for gravitational wave measurement. Both ST7-DRS and LTP have complete GRS and DRS systems and will be payloads on the LISA Pathfinder Mission, an ESA spacecraft (formerly known as SMART-2) scheduled for launch in 2007. ST7-DRS is developing and will demonstrate the Colloid Micro-Newton Thruster (CMNT) developed by Busek Co. in the US[5]. The LISA Pathfinder spacecraft will be equipped with both Field Emission Electric Propulsion (FEEP) and precision cold-gas microthrusters. This paper begins with a discussion of the microthruster requirements for LISA, describes the various microthruster technologies under development with a focus on the Busek CMNT, and finishes with a summary of the LISA microthruster technology development plan.

II. LISA Microthruster Requirements

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 (shown in Figure 2), thrust levels between 2-30 μN with a resolution of 0.1 μN and a thrust noise <0.1 μN/√Hz are necessary to meet these requirements. We now discuss each microthruster requirement in detail.

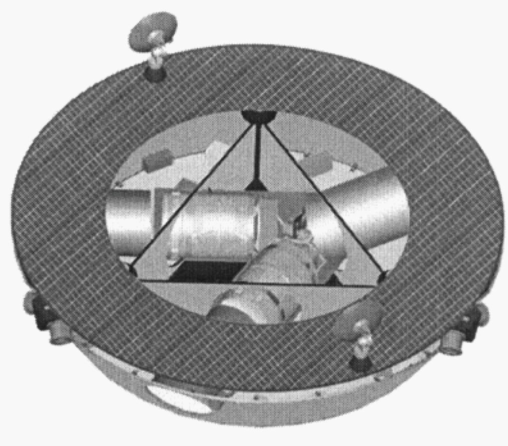

Figure2. LISA spacecraft conceptual drawing. Two of the three microthruster clusters are shown in the lower right and lower left on the outside of the spacecraft.

A. Thrust Range

During science operations, each microthruster shall produce approximately 9 μN of continuous thrust to compensate for the solar radiation pressure incident on the top of the spacecraft. The average or nominal thrust level may range from 6-12 μN as the spacecraft continues through its orbit, and the predicted thrust variation on time scales less than 1000 s is approximately +/- 4 μN based on current control laws. These levels could change, likely increasing, with changes to the spacecraft or thruster configuration. The levels could also decrease with an increase in the number of operating thruster heads, perhaps added for redundancy. Still, a maximum thrust level of $\geq$ 30 μN is required to handle the initial tip-off due to spacecraft separation from the propulsion module. Therefore, each microthruster shall have a thrust range of 2-30 μN.

B. Thrust Noise and Precision

The DRS control system regulates the thrust level to maintain the drag-free environment. To meet the acceleration noise allocation related to the relative motion of spacecraft and proof masses, the thrust noise shall be <0.1 μN/√Hz in the measurement bandwidth. This assumes weak coupling between the spacecraft and proof masses as well as a drag free control gain $>2.4\times10^5$ at 10^{-4} Hz. The drag-free control system also requires that the thrusters shall be controllable to a resolution of $\leq$0.1 μN in a 10 Hz control loop.

C. Thruster Lifetime and Propellant Usage

The thrusters shall be operated continuously for the life of the science operations (5-year operational life, 10-year extended mission). The amount of useable propellant shall be sufficient for the 10-year extended mission. The end-of-life performance of the thrusters shall still meet the thrust range, noise, and precision requirements discussed above.

For a nominal thrust of 9 μN for each of 6 thrusters over the 10-year lifespan, this requires a total impulse for the spacecraft of approximately 17,000 Ns (or roughly 2,800 Ns per thruster for 6 thrusters) and the corresponding amount of propellant based on the specific impulse (I_{sp}) of the microthruster. For example, a FEEP microthruster has an I_{sp} >6,000 s, requiring less than about 50 g of propellant per thruster. A cold gas thruster with an I_{sp} of ~60 s would require approximately 5 kg of propellant with more than 30 kg of propellant stored over the entire spacecraft, In any case, the propellant mass should be distributed and consumed symmetrically about the proof masses to maintain the self-gravity balancing within the spacecraft to the requirement specified by the appropriate acceleration noise allocation.

D. Thruster Plume Contamination and Spacecraft Interactions

To meet the top-level measurement sensitivity allocations, the optical subsystem shall have a transmission $\geq$0.3 and the stray light contribution to measurement phase error shall be <5 pm/√Hz. The thruster exhaust shall not contaminate the optics or contribute to stray light levels that exceed these requirements. The exact relation to the individual microthruster technologies depends on the propellant type and plume distribution.

Also derived from this acceleration noise allocation, the net magnetic field from all hardware components at the proof mass locations shall be < 10 μT. The magnetic field of the thrusters and associated electronics shall be sufficiently shielded to meet this requirement along with the other components of the spacecraft. In addition, thruster EMI/EMC shall not disrupt communications nor interfere with normal spacecraft operation. Finally, the thruster operation shall not significantly charge the spacecraft, likely requiring an electron-producing neutralizer for the FEEP and Colloid microthrusters.

All of these requirements have not been demonstrated by any single microthruster technology to date, specifically thruster lifetime. Although thrust range, noise, and precision have been measured in the laboratory[6-9], the requirement for 5 years of operation with 10 years of expendable propellant has proven difficult to demonstrate. A lifetime of greater than 4000 hours has not yet been demonstrated by any of the thruster technologies being considered. 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. Precision Microthruster Technology

Most of the thrusters being considered for LISA are electrostatic accelerators that require high-voltage power conditioning and a method to neutralize the accelerated ion beam. For these field emission microthrusters, the thruster package can be broken down into three pieces: emitter, neutralizer, and thruster electronics. Three types of emitters have the potential of meeting the LISA requirements: two are liquid metal Field Emission Electric Propulsion (FEEP) ion emitters with different electrode configurations and propellant types, and one is a colloid charged droplet emitter. Some aspects of each subsystem are similar and can be tested independently; however, most performance measurements must be taken on a complete package. The subsections below describe each of these systems as well as a precision cold gas thruster alternative for LISA.

A. Field Emission Electric Propulsion (FEEP) Microthrusters

The two types of FEEP thrusters, Cs-FEEP and In-FEEP, are shown schematically and in operation in Figure 3. The Cs-FEEP emitter is being developed by Centrospazio and ALTA in Italy[10] and has a slit geometry using cesium propellant. The In-FEEP emitter is being developed by Austrian Research Center (ARC) Seibersdorf Research[11] and uses a single needle geometry with indium propellant. FEEP thrusters operate by emitting and accelerating charged ions from a liquefied metal using a high voltage between 5 to 10 kV. As shown in Figure 3, the voltage is applied between extractor or accelerator and emitter electrodes and causes the liquid surface to deform into a "Taylor" cone where the electrostatic pressure is balanced by liquid surface tension. Beyond a propellant-dependent threshold voltage, the cone tip produces a jet of ions that are accelerated by the same applied voltage.

1. ALTA/Centrospazio Cesium FEEP Microthruster

Cesium propellant FEEP thrusters are typically constructed using a slit geometry. Multiple emission sites along the slit are fed by the capillary action of the cesium propellant. The number of emission sites depends on the slit length and thickness. With a micron-sized slit, each emission site operates at a small enough current so that droplet formation is kept to a minimum. The thrust level is controlled using the appropriate slit length and/or changing the applied voltage. Cesium also has a lower melting temperature (28° C) and higher vapor pressure (10^{-6} Torr at 28° C) compared to indium. Cesium FEEP thrusters have a slightly higher threshold voltage and operate between 6-12 kV with a specific impulse between 6000-12000 s. One drawback of Cesium FEEP thrusters is that the Cesium propellant must be isolated from air to avoid contaminating the propellant that reacts violently with water and

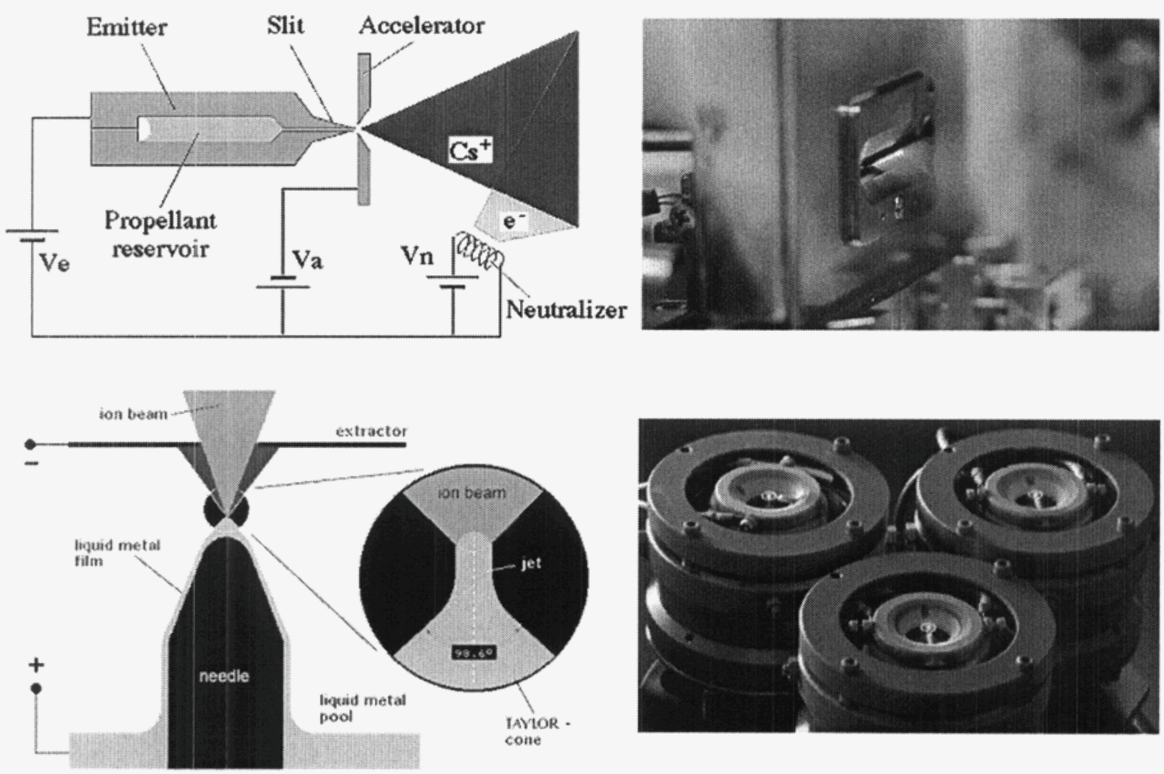

Figure 3. Schematics and pictures of a Cs-FEEP thruster developed by Centrospazio and ALTA (top), see Ref. 10, and three In-LMIS thrusters developed by ARC Seibersdorf Research (bottom), see Ref. 11.

oxygen. Such contamination may cause loss of efficiency, or blockage of the emitter altogether. Inert gas cavities with mechanical covers are typically used to isolate the propellant during ground processing. Another drawback of this type of emitter is the possible contamination of spacecraft components and loss of efficiency due to cesium droplet formation and evaporation. However, it is likely that contamination can be mitigated with physical barriers if necessary. Currently ALTA is developing Cs-FEEP thrusters for the Microscope and LISA Pathfinder Missions.

2. ARC Seibersdorf Research Indium FEEP Microthruster

Indium propellant FEEP thrusters use needles with 2-15 μm diameter tips or capillary tubes as single emission sites. To prevent droplet formation that occurs at high current operation, clusters of needles may be used to increase the number of emission sites. The thrust level is controlled by designing the accelerator with the appropriate number of needle emitters and/or by changing the applied voltage. Indium has a higher melting point (150° C) and a much lower vapor pressure (10^{-19} Torr at 150° C) compared to Cesium. Indium FEEP thrusters operate between 4.5-10 kV with a specific impulse between 4000-11000 s. Possible contamination and loss of efficiency due to droplet formation is the main drawback of the Indium FEEP. To date the In-FEEP thruster technology has accumulated the most operational hours on a single thruster in a series of tests, approximately 4000 hours of operation. ARC Seibersdorf Research has been developing the In-FEEP thruster for the GOCE and LISA Pathfinder missions, and is currently addressing concerns of decreasing propellant utilization over long duration operation.

Both FEEP thrusters require a heater to liquefy their propellant that generally uses <1 W of power and a cathode neutralizer that can use between 0.01-2W depending on the design. Because of a lower melting point, Cesium FEEP thrusters have a slightly higher thrust-to-power ratio, 17 μN/W, compared to Indium FEEP thrusters with 15 μN/W. Performance of both thrusters can be estimated using models of the discharge current and voltage along with an empirically verified assumption on the amount of beam divergence and droplet emission. Performance measurements and plume studies have been conducted using both thrusters, and both have the potential to meet all of the LISA requirements.

B. Colloid Micro-Newton Thruster

Colloid thrusters, currently under advanced development at Busek Co. Inc.[12,13], operate in a similar fashion to FEEP thrusters, as shown in Figure 4. The most important difference is that microscopic droplets (10 to 100 nm diam.) of a conductive liquid (doped glycerol, formamide, tributyl phosphate, or ionic liquid, for example) are extracted and accelerated instead of metal ions. 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 FEEP thrusters, colloid thrusters use an active propellant feed mechanism including a precision microvalve and a constant pressure bellows storage device that allow for two stages of electrodes: extraction and acceleration. The extraction voltage is kept constant (~2 kV) to eliminate neutral production and provide a stable source of charged droplets. The acceleration voltage can be varied from 0-10 kV to provide variable thrust and specific impulse.

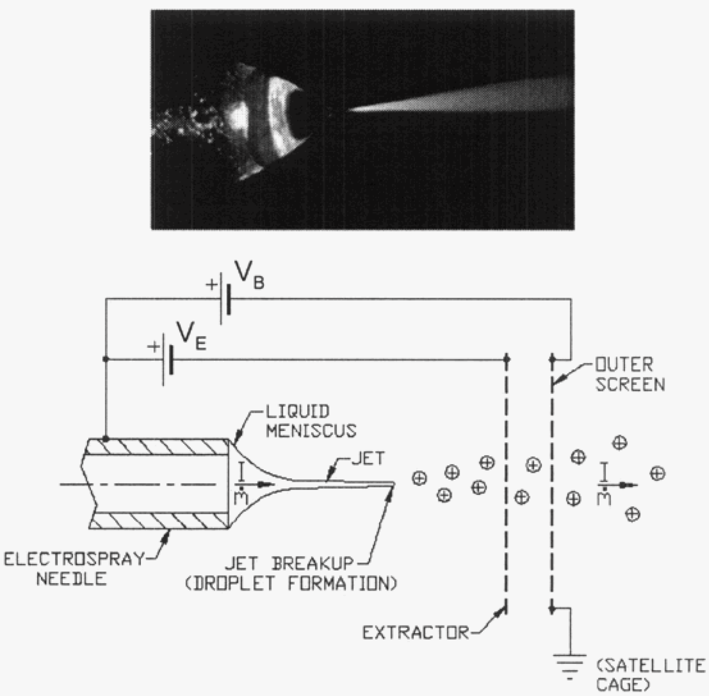

Figure4. Colloid microthruster electrospray using tributyl phosphate (EMI-Im does not produce visible droplets) and a schematic of the thruster emitter. Taken from Ref. 12.

Heaters to liquefy the propellant are generally not required, but may be needed to stabilize the physical properties of the propellant and reduce thrust noise. Colloid thruster performance is determined by the charge state of the droplets, the accelerating voltage, the propellant flow rate, and the ion beam divergence. Typical performance ranges from 0.5-30 μN per array with a specific impulse between 500-1500 s and a thrust-to-power ratio of 10 μN/W[5,9,12,13].

Out of all the field emission microthrusters, the Busek Colloid Micro Newton Thruster (CMNT) is the most developed in terms of demonstrated performance, completing a critical design review (CDR) for the ST7-DRS Project in May of 2004. Figure 5 shows one breadboard thruster in a cluster configuration produced before the ST7-DRS project preliminary design review (PDR). We will now discuss the subsystems of the Busek (CMNT) being developed for the ST7-DRS Mission that will also be useful for the LISA mission.

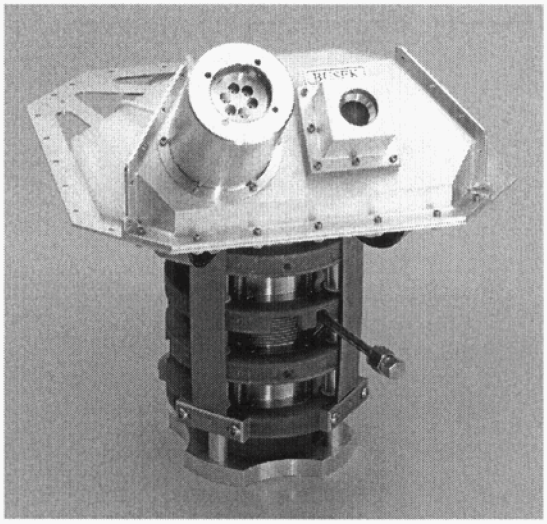

Figure5. Breadboard Busek Colloid Micro Newton thruster showing one complete thruster (thruster head, neutralizer, and propellant storage bellows unit) out of a quad configuration.

1. Thruster Head

The thruster head is comprised of a reservoir that feeds multiple capillary tube emitters. 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 from the extraction voltage and the charge to mass ratio of the droplets depends on the mass flow rate, the thrust of this type of colloid thruster is, $T \propto I^{1.5} \times V^{0.5}$, where I and V are the total beam current and voltage, respectively. This relation allows for dual control of the thrust. For small variations on short 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. Figure 6 shows 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 1 mHz[5,9].

For LISA (and more recently for ST7-DRS) the thruster head will require at 9 emitters to provide the range of 2-30 μN. 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. Busek has fabricated the new 9-emitter design and is beginning performance and long duration testing.

2. Propellant Feed System

1-ethyl-3-methylimidazolium bis(triflouro-methyl-sulfonyl) imide (EMI-Im) is an attractive propellant for colloidal microthrusters because of its high conductivity and negligible vapor pressure. It is classified as an ionic fluid, which is a salt that is liquid at or near room temperature. EMI-Im 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. A high conductivity propellant 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 throughout the mission is very important.

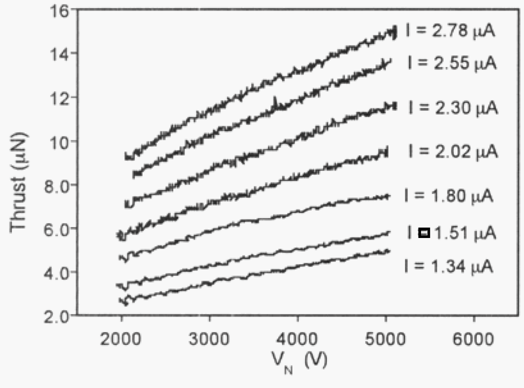

Figure6. Direct thrust measurements of Colloid Micro-Newton Thruster as a function of voltage and beam current. Taken from Ref. 5.

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

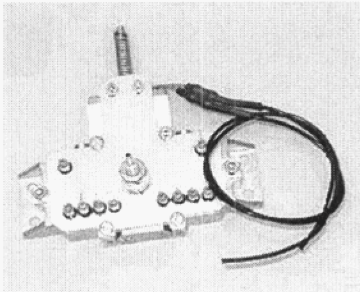

Figure 7. Polyflex precision cold gas microthruster.

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[14].

3. 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. For ST7-DRS, there will be one cathode neutralizer per thruster cluster, yet only one neutralizer is required to prevent spacecraft charging allowing for some redundancy. In fact, 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.

4. 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. There are also being used in long duration testing to demonstrate lifetime.

Conclusions from the Busek colloid microthruster work:

- Key DRS performance requirements were demonstrated
- Key components demonstrated and understood (thruster, neutralizer, μvalve, bellows, HV converters)
- The μvalve, CNT neutralizer, and thruster head are new technology
- System demonstration at breadboard level completed
- System life test of single needle (1.5*mission) completed
- Current effort focused on EM and Flight HW

C. Precision Cold-gas Microthruster

A number of companies that provide conventional cold gas thrusters are developing higher precision thrusters for drag-free and formation flying missions. Currently ESA and ESTEC are funding the development of a piezo-actuated cold gas concept by Polyflex Space Ltd. In Cheltenham, UK. Polyflex is now owned by Marotta Scientific Controls, NJ, USA. Shown in Figure 7, the Polyflex Piezoelectrically-Actuated Proportional Thruster (PAPT) has proportional flow control from 0 - 1 mN. An internal heater increases specific impulse to >70 s for gaseous nitrogen, and reduces effects of external temperature changes on thrust accuracy. The proportional control is provided by a piezo element, requiring less than 2 W for operation including the heater. Like most cold gas thrusters, it is capable of using a variety of gaseous propellants, but is also subject leaking over long durations and many valve cycles. Fortunately for LISA, the thruster will spend most of its time in operation, so leaks would only be important for redundant thrusters and isolation valves.

Still, no cold gas thruster has yet to demonstrate meeting LISA performance or lifetime requirements. Higher precision performance measurement tests are planned for the Polyflex PAPT, and it is believed that in the thrust range of 0-25 μN the resolution will be better than 0.2 μN. At higher thrust levels, the resolution likely becomes slightly worse, about 1 μN. Other microthrusters developed in the US by Moog and Vacco are also under development, but are not currently funded by outside sources. A precision cold gas microthruster will be tested in space on the LISA Pathfinder Mission.

IV. LISA Microthruster Technology Development

ESA and ESTEC are funding the development of the cesium FEEP thruster for several potential users including LISA and small commercial satellites. This has created a dual development path for this technology with different requirements and test priorities. Preparations for a lifetime demonstration test are currently underway.

The indium FEEP thruster is based on the flight-proven Indium liquid metal ion source (I-LMIS) that has been under development for roughly ten years. This technology has been used successfully for spacecraft potential control and as an ion source for a secondary ion mass spectrometer. It has over 1200 hours of operation in space on a number of missions including the GEOTAIL and CLUSTER-II spacecraft. ARC Seibersdorf Research is currently building up the propellant handling capability of their thruster designs as well as investigating multiple emitter configurations. They are also continuing to focus on long duration testing, recently starting a 1500-hour test on a new emitter designed and fabricated to stabilize the propellant utilization efficiency.

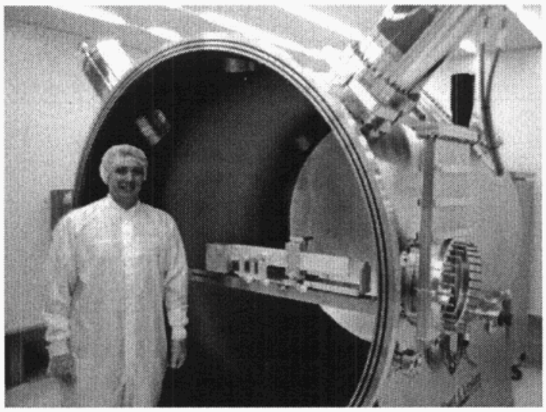

Figure 8. 2 m diam., 2 m long Ultra-high vacuum chamber at JPL showing Nano-Newton Thrust Stand inside chamber.

Busek has been developing colloid thrusters for nearly ten years and has already delivered breadboard models to NASA. The Busek CMNT will be developed and qualified to flight hardware status and demonstrated on the ST7-DRS Mission. Currently Busek is developing EM hardware and conducting long duration system-level testing of the CMNT, and will deliver two clusters of four thrusters to ST7-DRS in 2005. To date a 3000-hour test of a single needle thruster was complete without any observable degradation to the emitter tip. For LISA the propellant handling capability and possibly the specific impulse will need to be increased. Long duration testing of multiple emitter thrusters is key to demonstrating the technology to LISA requirements.

The precision cold-gas thruster will be demonstrated on the LISA Pathfinder Mission, although the thrust range and magnitude have not yet met current LISA requirements. Thrust noise has also not been measured, however, developments are underway to measure the performance of the thruster more accurately. The precision cold gas thruster is a less complex microthruster, that if it proves to meet LISA requirements, could be a possible alternative to field emission thrusters. Of course, these thrusters require more development, and technologists in both ESA and NASA will continue to monitor the progress.

In current plans, NASA is responsible for developing US microthruster technologies, and ESA is responsible for developing European microthruster technologies. In the US, since performance of the Busek CMNT has already been demonstrated to meet LISA requirements (expect for direct thrust noise measurements below 1 mHz), we will focus on long duration testing and verifying lifetime models.

V. Conclusions

We conclude that it is likely 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 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.

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Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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