SBIR/STTR
Small Business Innovation Research / Small Business Technology Transfer

NASA SBIR 2021 Phase I Solicitation

Z10.04 Materials, Processes, and Technologies for Advancing In-Space Electric Propulsion Thrusters

Lead Center: GRC

Scope Title:

Structurally Robust Magnetic Circuit Materials for Hall-Effect Thrusters

Scope Description:

Electric propulsion for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. Critical NASA electric propulsion needs have been identified in the scope areas detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state of the art (SOA) and quantitatively (not just qualitatively) describe anticipated improvements over relevant SOA materials, processes, and technologies that substantiate NASA investment.

To shape the magnetic fields needed for operations, Hall-effect thrusters utilize a magnetic circuit that also forms the thruster structure. The magnetic circuit components direct magnetic flux (typically produced by electromagnetic coils) and may experience operational temperatures in excess of 500 °C due to coil self-heating and the close proximity of plasma-wetted surfaces. Both low-carbon magnetic iron and cobalt-iron (Co-Fe) soft ferromagnetic alloys have been traditionally used in the role; low-carbon magnetic iron is typically cheaper with larger billet size availability, whereas Co-Fe soft ferromagnetic alloys are attractive due to high magnetic saturation and Curie temperature properties. As Hall-effect thrusters become larger to support future high-power applications, thruster components also experience and must survive increased inertial launch loads. To address this issue, prospective magnetic circuit materials are desired with improved structural strength compared to SOA options while retaining comparable or better magnetic and thermal properties. Prospective materials capable of being produced in machinable, large-diameter (i.e., >400 mm) solid billets—or that can be additively manufactured to achieve comparable sizes—are of particular interest. This solicitation seeks such prospective magnetic circuit materials suitable for Hall-effect thruster applications with the following properties:

- Mechanical: Meets or exceeds yield stress properties in Table X2.4 of ASTM Standard A801-14.
- Magnetic: Meets or exceeds properties in Appendix X1 of ASTM Standard A848-17.
- Thermal: Meets or exceeds Curie temperature of 770 °C.

Expected TRL or TRL Range at completion of the Project: 2 to 4
Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.2 Electric Space Propulsion
Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I:

1. Virtual kickoff meeting with the NASA Technical Monitor and potential stakeholders within the first month of the period of performance.
2. A final report containing test data characterizing key material properties as well as an assessment of material size scalability for future production.
3. Material samples that can be utilized for independent verification of claimed improvements over SOA materials.

Phase II:

1. Kickoff meeting with NASA Contracting Officer Representative (COR) and potential stakeholders within the first month of the period of performance.
2. A final report with test data either characterizing key material properties for produced large billets or demonstrating the functionality of one or more thruster components integrated with operating thruster hardware (in which partnering with electric propulsion developers may be necessary).

State of the Art and Critical Gaps:

SOA magnetic circuit materials used for Hall-effect thrusters are typically in two families: low-carbon magnetic iron or cobalt-iron (Co-Fe) soft ferromagnetic alloys (e.g., Hiperco®). While Co-Fe alloys are frequently preferred because of their magnetic and thermal properties, their available billet sizes do not readily accommodate larger thruster components needed for future high-power (i.e., >50 kW) electric propulsion applications. Low-carbon magnetic iron does come in large billet sizes, but past NASA high-power thruster development efforts (e.g., NASA-457Mv2 thruster) have identified potential risks regarding the survivability of components when subjected to launch loads. A magnetic circuit material that retains or exceeds the magnetic and thermal properties of SOA options while providing improved structural strength and scalability to large billet sizes is highly desirable to mitigate the risk.

Relevance / Science Traceability:

Both NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. Planetary spacecraft need the ability to rendezvous with, orbit, and conduct in situexploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; mission priorities are outlined in the decadal surveys for each of the SMD divisions (https://science.nasa.gov/about-us/science-strategy/decadal-surveys). For HEOMD, higher-power electric propulsion is a key element in supporting sustained human exploration of cislunar space.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in electric propulsion systems related to such missions. The roadmap for such in-space propulsion technologies is covered under the 2020 NASA Technology Taxonomy, with archival information contained in the 2015 NASA Technology Roadmap TA-2 (In-Space Propulsion Technologies).

References:

- D.M. Goebel and I. Katz, “Chapter 7: Hall Thrusters,” Fundamentals of Electric Propulsion: Ion and Hall Thrusters, https://descanso.jpl.nasa.gov/SciTechBook/SciTechBook.html
- ASTM Standard A801-14, “Standard Specification for Wrought Iron-Cobalt High Magnetic Saturation Alloys (UNS R30005 and K92650).”
- ASTM Standard A848-17, “Standard Specification for Low-Carbon Magnetic Iron.”
- D.F. Susan, et al., “Equal Channel Angular Extrusion for Bulk Processing of Fe-Co-2V Soft Magnetic Alloys, Part I: Processing and Mechanical Properties,” Journal of Materials Research, 33.15 (2018): 2168-2175.
- A.B. Kustas, et al., “Equal Channel Angular Extrusion for Bulk Processing of Fe-Co-2V Soft Magnetic Alloys, Part II: Texture Analysis and Magnetic Properties,” Journal of Materials Research, 33.15 (2018): 2176-2188.
- Z. Turgut, et al., “High Strength Bulk Fe-Co Alloys Produced by Powder Metallurgy,” Journal of Applied Physics, 103.7 (2008): 07E724.
- M.S. Masteller, J.W. Bowman, and L. Li, “High Temperature Aging Behavior of High Strength 49% Co-1.9% V-0.3% Nb-Fe Soft Magnetic Alloy,” IEEE Transactions on Magnetics, 32.5 (1996): 4839-4841.
- Decadal surveys for each of the SMD divisions, https://science.nasa.gov/about-us/science-strategy/decadal-surveys
- 2020 NASA Technology Taxonomy, https://www.nasa.gov/offices/oct/taxonomy/index.html
- 2015 NASA Technology Roadmap TA-2 (In-Space Propulsion Technologies), https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_2_in-space_propulsion_final.pdf

Scope Title:

High-Efficiency, Long-Life Hollow Cathodes

Scope Description:

Electric propulsion for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. Critical NASA electric propulsion needs have been identified in the scope areas detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state of the art (SOA) and quantitatively (not just qualitatively) describe anticipated improvements over relevant SOA materials, processes, and technologies that substantiate NASA investment.

Hollow cathodes in electric propulsion systems are utilized for generating discharge plasma and effecting plume neutralization in gridded-ion and Hall-effect thrusters. In SOA hollow cathodes, operating temperatures can range from 1,000 to 1,700 °C, and the cathode assembly may need to survive in excess of 10,000 operational hours and 10,000 thermal on-off cycles without failure. Critical NASA needs for hollow cathodes are:

1. High-current hollow cathodes with reduced power consumption. While SOA hollow cathodes can provide up to 25-A direct current necessary for electric propulsion applications, future interest in 100-kW electric propulsion systems will require a substantial increase in cathode current output to the range of 100 to 200 ADC. Scaling of current cathode architectures using various emitter technologies have achieved cathodes operating at >100-ADC emission current; however, these results typically require substantial increases in electrical power needed to drive plasma generation in the cathode and/or in an associated heating element for impregnate-based emission sources. Size increases for emitter and cathode, including heating elements, can also be significant to maintain the necessary thermal conditions for stable cathode life; the resultant larger sized cathodes can stress heater elements and limit their cyclic life—a concern facing cathodes utilizing LaB6 emitters. This solicitation seeks stable-performance, long-life cathode architectures that reduce power consumption (i.e., improve electrical efficiency) for >100-ADC emission current via improved heater design and operation, emitter material selection and configuration, lower plasma generation costs, reduced cathode thermal losses via conduction or radiation, etc.
2. Reduced-flow hollow cathodes in Hall-effect thrusters. Hollow cathodes used in Hall-effect thrusters are frequently operated with a fixed flow fraction relative to the anode flow; this approach is commonly utilized to reduce the cost and complexity of the propellant feed system. To promote efficient discharge plasma generation, these cathodes are typically operated with a higher than necessary propellant flow, which reduces specific impulse and may have negative impacts on cathode lifetime due to pressure-driven emission behavior. Past efforts to bifurcate the cathode flow between the cathode and an external (i.e., keeper or downstream region) contribution have demonstrated some success in providing stable and efficient cathode operation while reducing the total cathode (i.e., non-anode) flow fraction to less than 7% to 10% of the anode flow rate typically used in thruster operations. Being able to sustain thruster operations at such low total cathode flow fractions can result in significant propellant savings, particularly for high-power Hall-effect thrusters. This solicitation seeks readily adaptable methods to reduce cathode propellant flow needs (i.e., improve propellant utilization) without adversely affecting cathode and Hall-effect thruster stability and life.

Expected TRL or TRL Range at completion of the Project: 2 to 5
Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.2 Electric Space Propulsion
Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I:

1. Virtual kickoff meeting with the NASA Technical Monitor and potential stakeholders within the first month of the period of performance.
2. A final report containing quantitative analysis, modeling, or proof-of-concept test data addressing key risk factors associated with the technical approach and comparisons to SOA cathodes.
3. A cathode subsystem design that is compatible with high-power Hall-effect thruster concepts.

Phase II:

1. Kickoff meeting with the NASA Contracting Officer Representative (COR) and potential stakeholders within the first month of the period of performance.
2. A final report with test data supporting cathode performance, stability, and lifetime claims.
3. Cathode assembly hardware that can be utilized for independent verification of claimed improvements over SOA cathode assemblies.

State of the Art and Critical Gaps:

Future interest in 100-kW electric propulsion systems will require cathode current outputs in the range of 100 to 200 ADC. Experience to date with scaling current cathode architectures has resulted in cathodes that consume several kilowatts of power during operations. Such cathodes pose significant thermal management challenges for the thruster and concerns about the cathode's cyclic lifetime. Alternative cathode architectures that can significantly reduce power consumption are highly desirable to reduce risk for high-power electric propulsion applications.

Typical Hall-effect thrusters utilize a cathode flow fraction between 7% and 10% of the anode flow, with past studies of 50-kW-class thrusters at times requiring >10% cathode flow fraction to promote thruster stability at certain throttle points. For high-power electric propulsion systems utilizing Hall-effect thrusters, reducing cathode propellant flow needs can result in significant propellant savings on the order of hundreds of kilograms for typical NASA mission lifetimes. Past efforts to bifurcate the cathode flow between the cathode and an external (i.e., keeper or downstream region) contribution have demonstrated some success in providing stable and efficient cathode and thruster operations while achieving <7% total cathode flow fraction. Approaches for reducing cathode flow needs that can be readily adapted to SOA thruster architectures are highly desirable to improve system efficiency and lifetime.

Relevance / Science Traceability:

Both NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. Planetary spacecraft need the ability to rendezvous with, orbit, and conduct in situexploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; mission priorities are outlined in the decadal surveys for each of the SMD divisions (https://science.nasa.gov/about-us/science-strategy/decadal-surveys). For HEOMD, higher-power electric propulsion is a key element in supporting sustained human exploration of cislunar space.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in electric propulsion systems related to such missions. The roadmap for such in-space propulsion technologies is covered under the 2020 NASA Technology Taxonomy, with archival information contained in the 2015 NASA Technology Roadmap TA-2 (In-Space Propulsion Technologies).

References:

- V.J. Friedly and P.J. Wilbur, “High Current Hollow Cathode Phenomena,” AIAA 90-2587.
- M.A. Mantenieks and R.M. Myers, “Preliminary Test Results of a Hollow Cathode MPD Thruster,” IEPC 91-076.
- D.M. Goebel and E. Chu, “High Current Lanthanum Hexaboride Hollow Cathodes for High Power Hall Thrusters,” IEPC-2011-053.
- H. Kamhawi and J. Van Noord, “Development and Testing of High Current Hollow Cathodes for High Power Hall Thrusters,” AIAA-2012-4080.
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- D.M. Goebel, K.K. Jameson, and R.R. Hofer, “Hall Thruster Cathode Flow Impact on Coupling Voltage and Cathode Life,” Journal of Propulsion and Power, Vol. 28, No. 2, March-April 2012.
- S.J. Hall, et al., “Operation of a High-Power Nested Hall Thruster with Reduced Cathode Flow Fraction,” Journal of Propulsion and Power, July 2020.
- Decadal surveys for each of the SMD divisions, https://science.nasa.gov/about-us/science-strategy/decadal-surveys
- 2020 NASA Technology Taxonomy, https://www.nasa.gov/offices/oct/taxonomy/index.html
- 2015 NASA Technology Roadmap TA-2 (In-Space Propulsion Technologies), https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_2_in-space_propulsion_final.pdf