Space Propulsion and Power – Current Research Activities

Plasma Propulsion

Tightly Coupled Mechanistic Study of Materials in the Extreme Space Environment

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http://www.aero.psu.edu/levin/afosr_spp/spp.html

The intersections of these three disciplines will allow to characterize and quantify at a fundamental level the adverse particle-surface spacecraft environment in terms of surface absorptivity, surface degradation due to hypervelocity collisions with atomic oxygen, spacecraft charging, and solar cell array damage. Using the high fidelity surface material conditions controlled by the chemistry occurring within the first few monolayers, it will be sought to learn how to extend the time constants of a gas dynamic simulation from micro to milli-seconds to those relevant for predicting long term, mission factors. With a tightly coupled, mechanistic approach among researchers in – nonequilibrium gas dynamics, high fidelity gas-surface chemistry models , atomistic level determination of material response , and preparation and characterization of spacecraft material damage by small source ion bombardment. The major goal is to control, prioritize, and minimize spacecraft environmental issues, a general strategy crucial for small sized, resource-limited space platforms of high interest to the Air Force. The length scales of contamination vary by probably twelve orders of magnitude and the variation in time scales is similar. In the true space environment either chemical, electric, or hybrid propulsion sources, will not produce clean distributions of neutrals or ionic species, but, submicron size particulates will be included in contaminating effluent mix.

Plasma-Materials Interactions in Electric Propulsion

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http://web.mit.edu/aeroastro/labs/spl/research.html

The objectives of this research program are to: 1) generate detailed understanding of plasma sheaths over electrodes and stressed wall sections in plasma thrusters. 2) Predict and measure space and time--resolved plasma particle bombardment in these stressed areas. 3) couple this with precise data and first---principles calculations of wall response, including thermal,sputtering, evaporation in The presence of re-deposition and secondary electron emission and, in the case of electrodes, high current densities and associated phenomena. 4) Support and validate these calculations with materials science experiments and modeling. 5) Integrate the above into multi-scale codes for simulation of joint plasma/solid behavior at the device level. 6) Use the resulting insight to formulate candidate revolutionary concepts for novel wall inserts and electrodes. 7) Use these codes for optimization of complex devices, including novel wall inserts and electrodes for stressed areas. 8) Design and test devices with novel inserts, and electrodes to verify the resulting improvements in performance and lifetime, and iterate as needed

Comprehensive Study of Plasma-Wall Sheath Transport Phenomena

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http://mwalker.gatech.edu/afosr_group/index.html

It is proposed to conduct a highly integrated, cumulative research program to non-intrusively study the properties inside a plasma sheath and develop an understanding of the plasma-wall interaction and how both the sheath and the wall material affect the plasma as a whole. The research will study the most fundamental aspects of mass, charge, and energy transport in the plasma sheath, the relationship between plasma properties and wall surface modification as a function of wall material, and finally develop new material design methodologies.

Materials Analysis of Transient Plasma-Wall Interactions

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http://www.aa.washington.edu/research/plasmaDynamics/mse.html

With the discovery of a new class of electromagnetic pulsed plasma propulsion devices such as the Electrodeless Lorentz Force (ELF) Thruster, it is critical to characterize current, and develop and new materials for these systems that exhibit superior performance under the demanding conditions of space propulsion or directed energy. The aim is to discover and develop fundamental and integrated science among materials science, electric propulsion, and electro energetic physics that advances not only pulsed plasma thruster development but any future space power and propulsion concepts based on high energy density plasmas. Through a combination of experiment, surface analysis, numerical modeling and analytical study, the behavior of the plasma-material boundary under transient thermal convective and radiative loads will be investigated. Specifically, transient non-equilibrium plasma flows will be studied over a broad range of energy densities (1 kJ/m2 – 10 MJ/m2), on time scales of microseconds to milliseconds, using atomic and molecular propellants with masses from hydrogen to xenon. The chemical and physical effects of these flows on a range of insulative, conducting and composite materials will be quantified through detailed surface analysis on the micro, meso and macro scale. Both theoretical and numerical analysis of the particle dynamics that result from this research will be undertaken to understand and predict processes at the different time and length-scales corresponding to non-equilibrium conditions that will be relevant to not only space propulsion applications but to fields as diverse as plasma processing to nuclear fusion.

Fundamental study of interactions between pulsed high-density plasmas and materials for space propulsion

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https://www2.ae.utexas.edu/afosr_muec/

The overarching goal of the proposed research is to develop a fundamental understanding of plasma-materials interactions for pulsed thermal plasmas that are relevant to many space propulsion devices and to plasma-armature railguns. Approach is a closely integrated experimental and computational modeling research program to develop quantitative descriptions of physical and chemical processes at material surfaces. Principal focus will be to measure the onset (threshold) of material ablation and the rate of ablation once threshold conditions are exceeded. In addition to making precise measurements of material loss from the surface of the test samples, the group will study surface morphological, structural, chemical, and mechanical properties of the materials before and after plasma exposure. Relatively simple materials such as single-crystal silicon, aluminum oxide, and tungsten will be studied initially followed by an investigation of next-generation materials such as diamond bonded on novel substrates for their high ablation-resistance properties. The study will be anchored by a systematic physical modeling effort. Models of the capillary discharge and the railgun plasma armature will provide the species particle fluxes and energy fluxes incident on the material. Detailed atomic-scale and continuum-scale material models will quantify how particles and radiant fluxes cause morphological and chemical changes to the materials and result in ablation. The models will be tested by predicting results outside the range of conditions used in their development. Subsequent experimental data under these conditions will be used to assess the accuracy of these predictions.

Coherent Terahertz Acoustic Phonons: A Novel Diagnostic for Erosion in Plasma Thruster Discharge Chamber Walls

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http://science.marshall.edu/wilsont/AFOSR%20Overview.html

The study is based on the success in obtaining the first experimental evidence for the direct excitation of coherent nanosecond-pulsed high-frequency acoustic phonons in semiconducting doping superstructures by electromagnetic fields of the same frequency. Acoustic phonons are detected by a superconducting bolometer, with nanosecond resolution, at the appropriate time-of-flight across a (100) silicon substrate for ballistic longitudinal phonons when a silicon delta-doped doping superlattice is illuminated with grating-coupled nanosecond-pulsed 246-GHz laser radiation with an approximate power density of 1 kW/mm2. The absorbed phonon power density in the bolometer detector is estimated to be 10 μW/mm2, in agreement with theory. The absence of any detected transverse acoustic phonon signal by the superconducting bolometer is particularly striking – implying that coherent THz longitudinal acoustic phonons can be generated in silicon doping superlattices with negligible associated heat pulse generation. As a first application of this novel phonon source, team propose to undertake a study of the phonon transmission through thin layers of plasma thruster wall materials, in an attempt to quantify the level of defect generation resulting from plasma exposure. A key life-limiting mechanism for most plasma thrusters is their internal erosion through nonequilibrium plasma-material interactions mainly in the form of energetic ion impact. It is well known that lattice defects can strongly scatter acoustic phonons.

Electrosprayed Heavy Ion and Nanodrop Beams for Surface Engineering and Electrical Propulsion

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http://mae.eng.uci.edu/Faculty/MGC/HTML%20pages/AFOSR/Header.html

The goal is to study the production and energetic impact of electrosprayed nanodroplets and molecular ions, covering continuously the projectile size range from 1 nm up to hundreds of nm. The 1-20 nm size range is of great interest to achieve variable specific impulse (*Isp*) from 100 s to >1000 s in drop-based electrical propulsion, while pure molecular ion emission enables higher *Isp*. The 1-20 nm size range is of great interest to achieve variable specific impulse (*Isp*) from 100 s to >1000 s in drop-based electrical propulsion, while pure molecular ion emission enables higher *Isp*. The team recently demonstrated that electrosprayed nanodroplets are extraordinary sputtering projectiles (their sputtering rates exceed those of the state of the art ion beam technology by a factor between 100 and 600). Their impact on crystalline substrates produces new and unique phenomena such as surface amorphization and texturing of surfaces with controllable roughness. They have also investigated the emission of molecular ions from ionic liquids, many of which contain reactive species and display substantial etching. In addition, electrospray sources are ideal for focused beam applications. These findings lead to new opportunities in the fields of electric propulsion (achievement of improved and variable *Isp*, thrust and power density and propulsive efficiency, quantification of the lifetime of electrospray thrusters), MEMS and IC fabrication (broad-beam and focused-beam nanodroplet and ion sources for high speed beam milling and microrofabrication, reactive nanodroplet and ion etching, polishing of large and curved mirrors), surface processing (patterning of crystalline surfaces with amorphous layers, patterning of a textured surface with controllable roughness, strengthening of materials for increased thruster life, microscopy), and secondary ion mass spectrometry (SIMS) of organic surfaces. The goals of this study are to gain a detailed, firstprinciples understanding of the production of nanoprojectiles, their interaction with surfaces, and the investigation of the surface processing and propulsive applications outlined above.

Michigan/AFRL Center of Excellence in Electric Propulsion

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http://pepl.engin.umich.edu/maceep.html

To advance the state-of-the-art of current or near-term systems, and to accelerate the development of more advance propulsion systems, The University of Michigan, Michigan Tech, Penn State, UCLA and Colorado State have teamed together to establish the Michigan/Air Force Research Laboratory Center of Excellence in Electric Propulsion which will bring together researchers from the Air Force Research Laboratory and the five research universities identified above in a coordinated and synergistic manner to help enable the Air Force to reach its performance goals for EP systems such those in the Beyond-IHPRPT roadmap. 1) Plasma Propulsion Systems, with a focus on characterizing field-reversed configuration (FRC) thrusters, developing pulsed inductive thrusters (PITS), and the fundamental studies of cross-field electron transport, remote thruster identification, and in situ thruster wall erosion physics of state-of-the-art Hall-effect thrusters. 2) Electrospray Propulsion, with a focus on colloid thrusters, field emission thrusters including nanoFET, and the evaluation of the ionic liquid as a potential propellant 3) Modeling and Simulation with a focus on plasma and electrospray thruster physics and life modeling, thruster plume modeling, and facility effects 4) Power Processor Units, with a focus on new topologies, the development of new computational PPU design tools/methodologies, and the interaction between the PPU and thruster.

Young Investigator Program:

Energy Conversion and Loss Processes in heavy gas, field-reversed configuration Electric Thruster Plasma

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http://campus.mst.edu/aplab/MPX.html

The proposed project uses an integrated experiment and modeling approach to investigate the fundamental energy conversion and loss processes of heavy gas FRC formation. There are four main tasks: 1) slow bias field plasma study, 2) design and upgrade test article for FRC study, 3) verify FRC formation in the device, and 4) characterize ionization, heating, radiation, and transport processes for heavy gas FRCs. Experimental measurements on a FRC test article and numerical plasma simulations with the unsteady MHD code NIMROD and collisional radiative code PrismSPECT will be used to gain fundamental understanding of the ionization, plasma heating, radiation, and transport processes that limit heavy gas FRC formation efficiency.

Near-Surface Cusp Confinement of Micro-Scale Plasma

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The primary hypothesis of this work is that a significant improvement in the understanding of the plasma structure very near the surface of micro-scale electron and plasma discharge devices is necessary to allow designers to take full advantage of the benefits of permanent magnet confinement. In particular, it is of interest to know to what extent micro-scale discharges can benefit from the relatively high magnetic field strength that can be attained at small scales using permanent magnets. The overall intent of this research is to investigate the near-surface dynamics and structure of plasma confined by highly divergent magnetic cusps that terminate on a conducting surface. The knowledge, tools, and analytical formulae derived from this combined experimental and computational analysis will be used to develop efficient micro-scale plasma devices.

Propellant-free Spacecraft Relative Maneuvering via Atmospheric Differential Drag

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http://afosr-yip.riccardobevilacqua.com/index.html

This research seeks to greatly extend the knowledge about spacecraft/atmosphere interactions in Low Earth Orbits (LEO). This, in turn, will enable propellant-free multi-spacecraft missions, exploiting atmospheric Differential Drag (DD). In addition, it will provide a superior platform for onboard estimation of atmospheric neutral density. DD is a non-chemical, propellant-free new concept to generate relative control forces at LEO. This study will build the knowledge necessary for a new way to model and exploit the atmosphere, paving the way for a first demonstration flight. The research objectives are: 1) to create a theoretical framework for understanding and designing analytical, DD-based guidance trajectories for new multi-spacecraft missions; 2) devise a feedback control strategy for accurate tracking of the guidance in a real flight environment; 3) provide an important contribution to atmosphere modeling and particularly atmospheric neutral density estimation; 4) design a spacecraft capable of DD control.

Chemical Propulsion

Nanoenergetics and High Hydrogen Content Materials for Space Propulsion

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www.emcl.psu.edu

There exists a need to thoroughly identify, and investigate novel propellants in order to achieve desired combinations with higher density, higher specific impulse, and better thermal properties. Alternatives to such propellant systems as LOX/LH need to be explored in a systematic manner. Additives to hydrogen or the use of hydrocarbons may allow upper stages to deliver a better overall performance with reduced volume and cost.2 One such fuel with desirable properties which may replace LH is liquid methane. In the past forty years, LOX/methane is the only new propellant combination that has been adopted for flight engines in the United States. Such a lack of innovation highlights the fact that the advancements in propellant technology have been found wanting for a long time. The goals of the research are to develop the fundamental understanding needed to exploit novel propellants based on new technologies from the field of nanotechnology as well as from those related to a hydrogen fueled economy. The former can offer new composite material designs and potential benefits in performance, e.g., higher burning rates and shorter burning times. The latter is of interest because of the inherent multifunctional advantages of molecular hydrogen for a propulsive fuel and product gas for power applications.

Reduced Basis and Stochastic Modeling of Liquid Propellant Rocket Engine as a Complex System

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http://sites.uci.edu/afosrproject/

The research will explore, develop, and apply interrogation techniques using full scale liquid propellant rocket motor combustion instability models. The work is intended to explore the source of the unstable behavior and to suggest control methodologies. Here, “source” will refer to both the mechanism by which an instability is triggered and the mechanism which sustains or drives the ultimate nonlinear oscillation. Both mechanisms will certainly involve some of the same types of physical and chemical processes; however, the organization and relative importance of the processes will likely differ within the two mechanisms. Identify the mechanical-thermal-chemical sources that serve as initiators (triggers) of triggered nonlinear instabilities in the chamber. Relate initiation to establishment of the nonlinear resonant oscillation, growth of the oscillation amplitude, and the transient to the limit-cycle. The overall objectives of this study are to: 1. Identify the mechanical-thermal-chemical sources that serve as initiators (triggers) of triggered nonlinear instabilities in the chamber. Relate initiation to establishment of the nonlinear resonant oscillation, growth of the oscillation amplitude, and the transient to the limit-cycle. 2. Identify the mechanical-thermal-chemical sources that serve as drivers or sustainers of the limit-cycle oscillation and the transient to the limit-cycle . 3. Develop statistical and in particular machine learning methodologies that are data driven and automatically can identify patterns likely to trigger nonlinear instabilities. The results of the research supporting Objectives 1 and 2 will be instrumental in selecting appropriate inputs and possibly specialized structure for the learning machines. 4. Identify possible directions for strategies that can inhibit the triggering action and/ or the growth of the oscillation following the triggering action. 5. Develop and demonstrate reduced basis method-based efficient complex system analysis methodology to predict processes in the chamber under both stable and unstable conditions 6. Implement and establish a hybrid reduced basis method -LES capability to simulate in a cost effective manner multi-injector liquid rocket engine with full coupling between the injectors and the combustor flow fields 7. Develop and establish methodologies and integrate emerging methodologies that not only aid in addressing Objectives 1, 2, and 3 but also offer promise for addressing other applications beyond liquid propellant rocket engine instability.

Effects of Increased Energy and Particulate Damping on Rocket Engine Combustion Stability

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To overcome the performance limitation and maintain the benefits of liquid fuels, compatible and energetic additives could be used. However, the effect of increased energy release on combustion instability must be a major concern. The study is a scientific investigation into the combined effects of mean heat distribution and temporal combustion response, and particle damping effects, on liquid rocket engine combustion instabilities. The work seeks to provide fundamental understanding that will enable determinations of the types of energetic additives that can simultaneously improve performance and lead to greater margins from combustion instability. Specifically, we seek to understand how changes in rates of combustion kinetics and energy addition affect combustion instability in an unstable model rocket combustor, how energetic additives change the burning characteristics of fuel drops and how those changes affect the instability characteristics, and how particles can be used to damp out the instability.

Theoretical, Numerical, and Experimental investigations of the fundamental processes that drive combustion instabilities in liquid rocket engines

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http://www.comblab.ae.gatech.edu/AFOSR/home.html

Currently, elucidation of the mechanisms that drive combustion instabilities in liquid rockets is practically impossible because small scale rigs can't simulate conditions in full scale rockets and testing full scale rockets is prohibitively expensive. This study is investigating an experimental approach would allow simulating the operating conditions in a full scale, unstable, liquid rocket in a small scale experimental setup. Once developed, this experimental setup and associated numerical and theoretical studies will provide knowhow and tools for studying the fundamental processes that drive combustion instabilities in different liquid rockets. Specifically, these studies will investigate the driving provided by different liquid rocket designs to evaluate their relative stability. The investigated experimental setup will simulate a small region in the full scale rocket motor. It will consist of an injector plate having one or more injectors, an exhaust nozzle and actively controlled boundaries that will employ speakers to simulate the impedances of these boundaries during an instability in the actual engine. These impedances will be determined by "controllers" that employ acoustic models of the full scale rocket. The experimental setup will also have transducers ports and windows for optical diagnostics of the combustion process. These diagnostics will consist of, e.g., dynamic pressure transducers, PIV, OH PLIF and radicals chemiluminescence. Experiments will be performed with different injectors under different operating conditions. By comparing the growth rates and limit cycle amplitudes of the instabilities in the developed setup it would be possible to determine the relative driving provided by the studied injector designs and distributions, and the dependence of the observations upon operating conditions. Additionally, comparisons of measured data with the predictions of the numerical simulations and theoretical analyses, which will investigate low order models, will determine the fidelity of these analytical tools and whether they incorporated into rocket design protocols that predict the engine stability.