REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
January 2015	Technical Paper and Briefing Charts	January 2015-February 2015

4. TITLE AND SUBTITLE
The Air Force Research Laboratory's In-Space Propulsion Program

5a. CONTRACT NUMBER
In-House

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Beal, Brian

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
Q18B

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory (AFMC)
AFRL/RQRS
1 Ara Drive.
Edwards AFB, CA 93524-7013

8. PERFORMING ORGANIZATION REPORT NO.

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory (AFMC)
AFRL/RQR
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RQ-ED-TP-2015-008

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution A: Approved for Public Release; Distribution Unlimited.

13. SUPPLEMENTARY NOTES
Technical paper and briefing charts presented at 38th Annual AAS Guidance & Control Conference, Breckenridge, CO; 2 Feb 2015. PA#15047

14. ABSTRACT
The Air Force Research Laboratory's In-Space Propulsion Branch (AFRL/RQRS) has primary responsibility for development and maturation of spacecraft propulsion technologies in support of future Air Force missions. AFRL has active research programs in both advanced chemical propulsion and electric propulsion. Advanced chemical propulsion programs are developing thrusters that operate on a class of non-toxic, energetic propellants that offer performance surpassing that of state-of-the-art hydrazine systems. AFRL's electric propulsion efforts are focused on sustainment of Hall effect thruster technology and development of higher-performing, lower-mass alternatives such as electrosprays and field reverse configuration thrusters. Fundamental relations showing the influence of key technology metrics such as mass and specific impulse on mission-level performance are presented to illustrate the rationale behind AFRL's technology development strategy.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Brian Beal
a. REPORT	b. ABSTRACT	c. THIS PAGE	SAR	27	19b. TELEPHONE NO *(include area code)*
Unclassified	**Unclassified**	**Unclassified**			661-525-6660

(Preprint) AAS 15-052

THE AIR FORCE RESEARCH LABORATORY'S IN-SPACE PROPULSION PROGRAM

Brian E. Beal[*]

The Air Force Research Laboratory's In-Space Propulsion Branch (AFRL/RQRS) has primary responsibility for development and maturation of spacecraft propulsion technologies in support of future Air Force missions. AFRL has active research programs in both advanced chemical propulsion and electric propulsion. Advanced chemical propulsion programs are developing thrusters that operate on a class of non-toxic, energetic propellants that offer performance surpassing that of state-of-the-art hydrazine systems. AFRL's electric propulsion efforts are focused on sustainment of Hall effect thruster technology and development of higher-performing, lower-mass alternatives such as electrosprays and field reverse configuration thrusters. Fundamental relations showing the influence of key technology metrics such as mass and specific impulse on mission-level performance are presented to illustrate the rationale behind AFRL's technology development strategy.

INTRODUCTION

The Air Force Research Laboratory (AFRL) is the technology development arm of the United States Air Force (USAF). Its mission is to "lead the discovery, development and integration of affordable warfighting technologies for our air, space, and cyberspace force." AFRL consists of approximately 10,000 total employees, including civil servants (45%), uniformed military members (15%), and support contractors (40%). Of the >6000 AFRL members who are scientists or engineers, 80% have at least a Master's degree with approximately 1/3 possessing a doctorate in their area of expertise. AFRL personnel and activities are dispersed among the locations shown in Figure 1.

AFRL's In-Space Propulsion Branch (AFRL/RQRS), located at Edwards Air Force Base, is responsible for research, development, and maturation of spacecraft propulsion technologies for use on future Air Force and Department of Defense (DoD) spacecraft. The branch's primary customer is Air Force Space Command (AFSPC). Technology transition is a critical part of AFRL's mission, and it is often accomplished via space experiments or incorporation of AFRL-developed hardware or expertise into spacecraft acquisition programs. RQRS has a typical annual project budget of roughly $2-3M, a large portion of which funds approximately 15 on-site contractors that support the activities of 16 civil servants and 3 military members.

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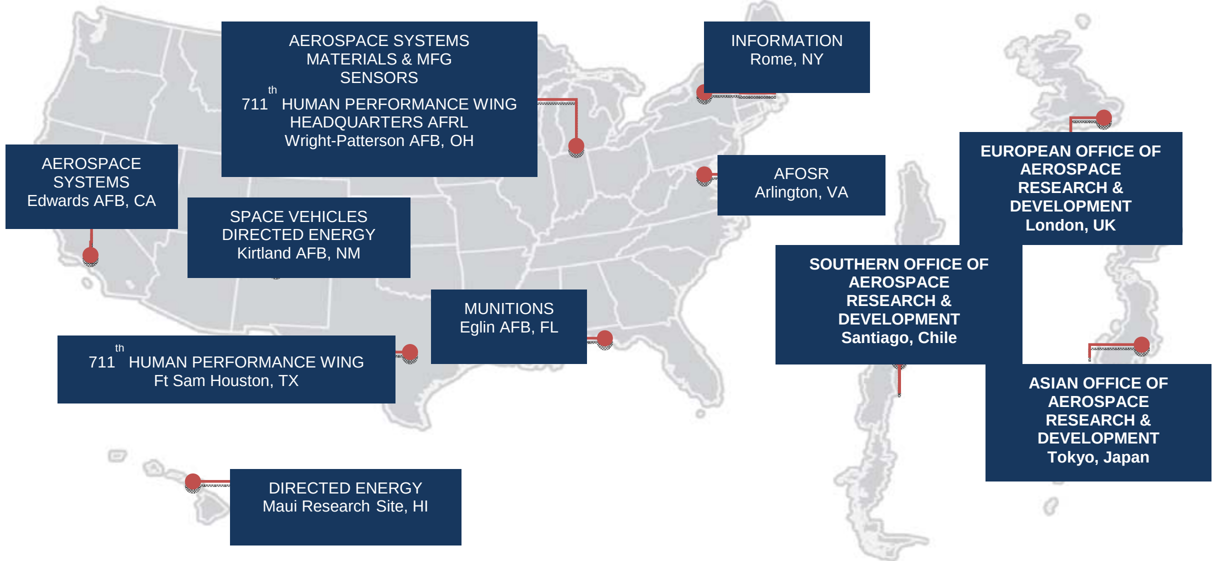

Figure 1. AFRL locations and major offices.

TECHNICAL GOAL DEVELOPMENT

AFRL's spacecraft propulsion technology development goals are derived from two primary sources. The first is the AFSPC Core Function Support Plan (CFSP), which provides high-level guidance regarding capability advances that are required in both specific components (e.g. transceivers, detectors, etc.) and pervasive capabilities (e.g. thermal control, propulsion, etc.). Using CFSP guidance, a team of AFRL and Space & Missile Systems Center (SMC) personnel work together to maintain an SMC "Tech Needs" document that establishes quantitative performance targets for individual systems and subsystems.

The second source of technology goals is the Rocket Propulsion for the 21st Century (RP21) program, which is the successor to the Integrated High Payoff Rocket Propulsion Technologies (IHPRPT) effort. RP21 is a government-industry consortium that is co-chaired by senior Department of Defense and NASA officials, who are supported by a steering committee consisting of industry representatives. Its purpose is to coordinate mutually beneficial rocket propulsion investment across both the defense and civil sectors of the government and industry base. The program operates on a philosophy of "technology push," meaning that it is intended to advance the overall state of U.S. rocket propulsion capabilities, rather than to develop point designs that are optimized for a particular launch vehicle or spacecraft. This is facilitated by choosing a baseline system representing a given technology area and then specifying quantitative improvements that are desired in certain metrics and timeframes. For example, a baseline liquid rocket engine could be identified as the Space Shuttle Main Engine and a 50% increase in mean time between failures by 2020 could be specified as a goal.

While the SMC Tech Needs and RP21 goals are separate products, there is substantial overlap between the two. AFRL plays a fairly large role in development of both. One of the primary ways in which AFRL contributes is by performing rudimentary mission analyses to determine which propulsion parameter improvements would provide the greatest payoff at the mission level for certain classes of spacecraft, as opposed to an individual spacecraft design. For instance, it is common knowledge that a majority of USAF spacecraft operate in geosynchronous earth orbit (GEO). A common mission scenario that is often considered is therefore the transfer of a spacecraft from an initial injection orbit to GEO using electric propulsion, as performed by the AEHF-1 spacecraft.[1,2] The fine details required to conduct such a transfer are fairly complicated and depend on many parameters including launch date, spacecraft steering and attitude control algorithms, and similar design-specific nuances. The general mission performance and trends, however, can be readily studied using two simple relations given in Equations (1) and (2). Here η represents the efficiency of the propulsion system, g is the gravitational acceleration (9.81 m/s^2), I_{sp} is specific impulse, and T/P is the thrust-to-power ratio. The delivered payload mass fraction is represented by m_{pay}/m_o, α is the specific power of the combined power and propulsion subsystems (W/kg), ΔV is the velocity increment associated with a given orbit change, and Δt is the allotted thruster firing time to complete the transfer. In this formulation, the delivered spacecraft mass, mpay, is defined as the spacecraft mass delivered to the destination orbit less the dry mass of the propulsion and power subsystems.

$$\eta = \frac{gI_{sp}}{2}\left(T/P\right) \tag{1}$$

$$\frac{m_{pay}}{m_0} = \frac{\left(gI_{sp}\right)^2 + 2\eta\alpha\Delta t}{2\eta\alpha\Delta t \exp\left(\dfrac{\Delta V}{gI_{sp}}\right)} - \frac{\left(gI_{sp}\right)^2}{2\eta\alpha\Delta t} \tag{2}$$

A simple analysis of a low Earth orbit (LEO) to GEO transfer using only Equations (1) and (2) is shown in Figure 2 for an allotted thruster firing time of 90 days and several combinations of electric propulsion (EP) system efficiency and specific mass, α. This figure shows several mission-level performance benefits that can be obtained by improving power and propulsion subsystem parameters from typical state of the art values of roughly α=50 W/kg and η=60%. First, as expected, improving the efficiency of the EP system from 60% to 80% has a beneficial effect on delivered spacecraft mass. Second, and perhaps less obvious, increases in the specific power of the propulsion and electrical subsystems have a substantially greater impact on mission performance than do increases in thruster efficiency. Finally, for a 90-day LEO-GEO transfer and specific powers achievable by current and near-term technologies, the optimum thruster specific impulse is in the 1500-3000 second range. Longer allowable trip times tend to favor higher specific impulses. Shorter trips, more energetic starting orbits, and practical limits on spacecraft power level for specific missions (e.g. due to cost, size, etc.) tend to reduce the optimum specific impulse.

A family of analyses like the one described above, as well as analogous assessments for chemical propulsion and other applications, are used to aid the formation of the specific technology goals pursued by AFRL/RQRS.

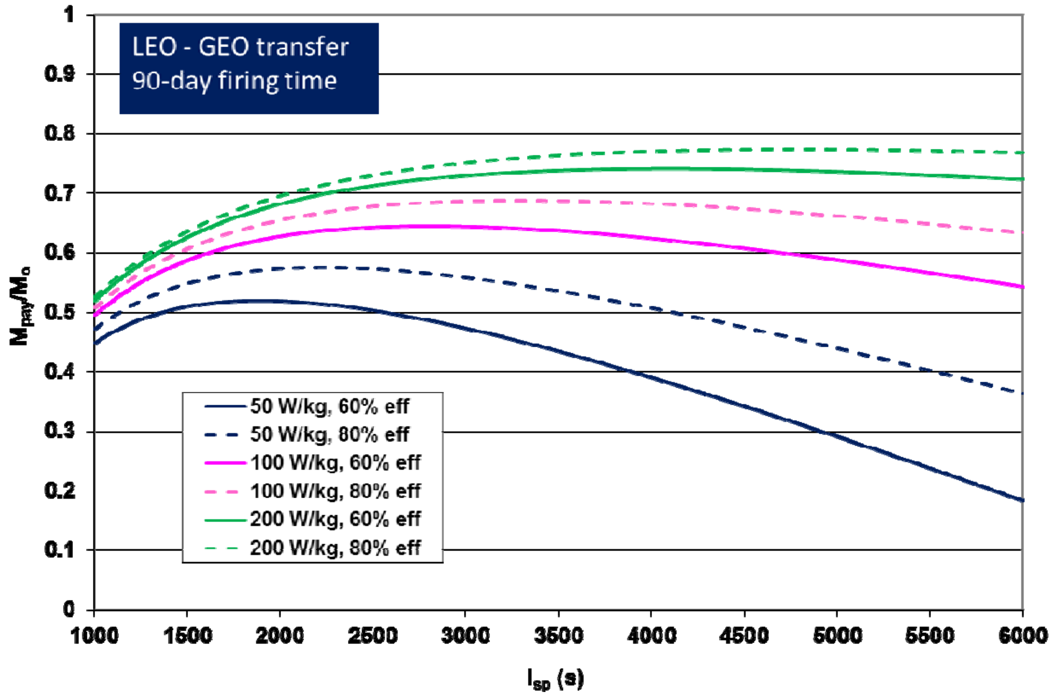

Figure 2. The delivered mass fraction for a 90-day LEO to GEO transfer using electric propulsion for several values of Isp, α, and η.

TECHNOLOGY PORTFOLIO

AFRL/RQRS's current efforts can be broadly categorized into 6 general areas: advanced chemical propulsion, electric propulsion, modeling & simulation, plume phenomenology, multi-mode propulsion, and flight experiments. In brief, the primary objectives of these activities are as described in Table 1. The primary activities within the two device development categories, EP and advanced chemical propulsion, are further elaborated below.

Table 1. AFRL In-Space Propulsion activities and objectives.

Activity	Objectives
Electric Propulsion	- Develop new technologies with increased efficiency and decreased dry mass relative to state-of-the-art Hall thrusters - Develop electric thrusters capable of operation on traditionally chemical propellants (e.g. hydrazine, energetic ionic liquids, etc.) - Sustain Hall thruster technologies and optimize them for specific applications when requested by DoD customers
Advanced Chemical Propulsion	- Develop monopropellant thrusters that operate on non-toxic, high-density propellants and provide higher specific impulses that hydrazine thrusters - Understand and, if necessary, reduce the minimum impulse bit achievable by small monopropellant thrusters in order to support emerging missions
Multimode Propulsion	- Develop flexible systems capable of either high-thrust/low-Isp (i.e. chemical thruster performance) or low-thrust/high-Isp (i.e. EP performance) using a common propellant
Modeling & Simulation	- Develop and maintain an adaptable modeling framework capable of predicting performance, plume properties, and spacecraft interactions for a wide variety of propulsion devices.
Plume Phenomenology	- Create remote and in-situ plume diagnostic capabilities, as well as the analytical models necessary to interpret them, to enhance knowledge of both experimental and operational propulsion devices.
Flight Experiments	- Perform in-space experiments to validate aspects of propulsion system operation and obtain unique information that cannot be obtained in ground testing - Provide subject matter expertise to government customers using new or non-traditional propulsion schemes

Advanced Chemical Propulsion

AFRL's primary activities in the field of spacecraft advanced chemical propulsion are focused on development of hydrazine-replacement technologies. Over the last decade, a class of reduced toxicity, high performance monopropellants consisting primarily of ionic liquids (low melting point salts) has been developed to meet the IHPRPT goal of a 50% increase in density-impulse over hydrazine.[3] One of these propellants, known as AF-M315E, was selected for maturation and technology transition based on both its high performance and its very benign safety properties. In particular, AF-M315E exhibits essentially no vapor toxicity, acceptable thermal stability, and is insensitive to electrostatic discharge at spark energies of 1.0 joule.[3] It has been categorized as a slight irritant per the Dermal Irritation Descriptive Classification and a non-irritant according to the European Dermal Evaluation Criteria for erythema and edema as opposed to hydrazine, which is such a strong irritant that it is categorized as corrosive.[3] Use of AF-M315E is expected to reduce costs and timelines for launch site operations because it can be handled in minimal protective equipment (e.g. shirtsleeves) rather than requiring full SCAPE suits and breathing apparatus.

After several years of steady progress in development of thrusters capable of operating on AF-M315E, and withstanding the intense chamber conditions that enable high-performance, thrusters using this propellant have been selected for flight demonstration as the highlight of NASA's Green Propellant Infusion Mission (GPIM).[4] GPIM will demonstrate thrusters operating at both the 1N and 22N thrust levels, which represent the majority of the monopropellant thruster market.[5] Ball Aerospace is the prime contractor for GPIM, Aerojet-Rocketdyne is building the propulsion system, and AFRL is furnishing the AF-M315E propellant as well as performing the propellant loading operations.

In addition to efforts to transition AF-M315E to operational use, AFRL/RQRS work in advanced monopropellants also includes ongoing development of even higher-performance propellant formulations, creation of improved thruster test facilities and procedures, and adaptation of monopropellant devices to emerging mission classes requiring very small impulse bits.

Electric Propulsion

Hall thrusters represent the vast majority of AFRL electric propulsion work over the last 15 years. This work has included both assessment of industry-initiated Hall thrusters as well as development of government-owned designs, and it has resulted in extensive experience in Hall thruster design, build, test, and flight. Hall thrusters are the baseline against which we assess new EP technologies. Typical examples of flight-proven, state-of-the-art thrusters include the Aerojet-Rocketdyne XR-5 (formerly known as the BPT-4000) and the Busek BHT-200.

The High-Power Propulsion System (HPPS) program was an AFRL-funded effort to improve the performance of Hall thrusters across a wide range of operating conditions. The program tested over 20 parametric variations examining specific aspects of thruster design and operation. It was successful in achieving an expanded range of specific impulse (1000-3000 seconds), improving thruster efficiency relative to the baseline, and demonstrating the ability to scale a given thruster design to various power levels while maintaining favorable performance characteristics. In addition to advancing the thruster technology, AFRL and Aerojet, in collaboration with NASA JPL, developed a brassboard modular power processing unit (PPU) capable of outputting voltages ranging from 125 to 800 DCV while accepting a wide range of input voltages.[6] Figure 3 shows images of the HPPS thruster before and during firing for two different configurations.

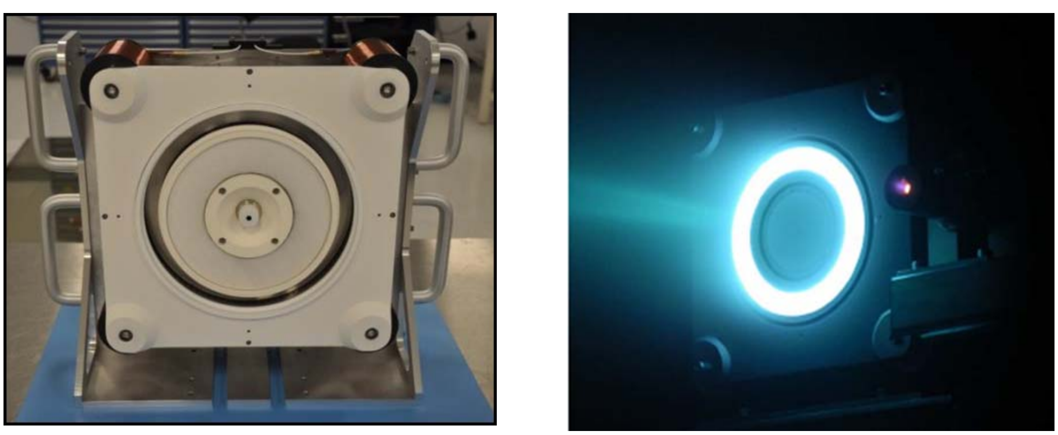

Figure 3. The HPPS Hall thruster.

In addition to the HPPS program, over the last several years AFRL has also conducted or funded research on several other advancements in the field of Hall thrusters. First, the H6 Hall thruster was initiated as a developmental testbed allowing for rapid and inexpensive reconfiguration, as well as establishment of internal and external diagnostic techniques.[7,8] Additionally, a number of Hall effect thrusters have been demonstrated on condensable propellants such as iodine, bismuth, or magnesium.[9,10,11] Such developments may enable niche benefits such as reduced propellant cost, increased thrust-to-power, or reduced propellant storage volume. For reduced-mass, high-power operation, or applications requiring an extremely wide throttling range, AFRL has supported development of nested channel thrusters such as those shown in Figure 4.[12] Finally, a series of high-speed plasma diagnostics have been developed to better understand the internal physics of EP devices.[13]

Considering the current state of the technology, AFRL now assesses Hall thrusters to be a mature technology that is ready for routine use on DoD spacecraft. As such, AFRL's work on Hall thrusters has shifted away from basic research & development, and toward technology sustainment. Ongoing efforts involve improving qualification test methodologies, assisting DoD customers in applying Hall thruster technology to particular missions, and, where possible, implementing modest performance improvements.

As AFRL gradually moves away from Hall thrusters and toward next-generation EP systems, there are two technologies in particular that are currently being pursued for satisfaction of RP21 goals. The first is the field reverse configuration (FRC). FRC's are pulsed, electromagnetic devices that utilize the interaction between induced plasma currents and applied magnetic fields to accelerate a magnetically-isolated plasma structure called a plasmoid.[14] Figure 4 shows FRC thrusters in operation. To date, FRCs have been demonstrated in both single-pulse and quasi-steady operation. Performance measurements of an FRC thruster built by MSNW, Inc. are scheduled to be conducted at AFRL in early 2015.

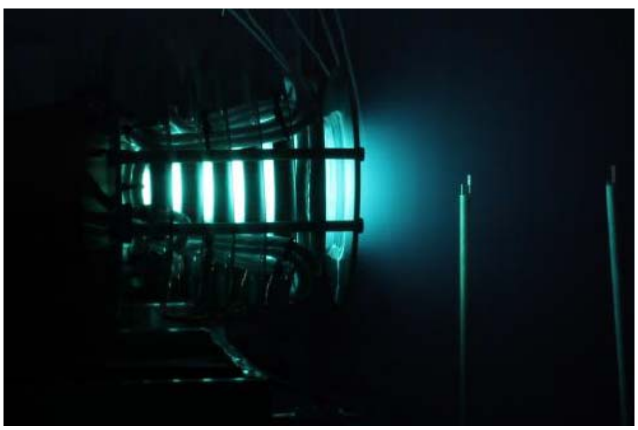
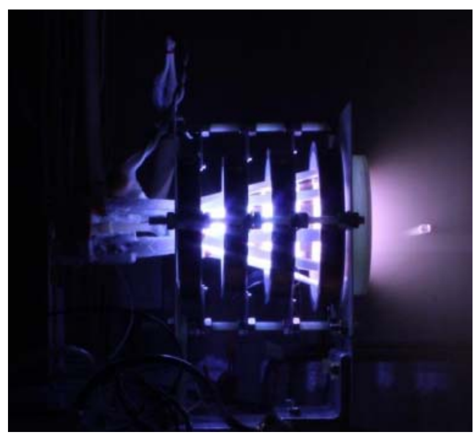

Figure 4. FRC thrusters in operation.

The primary characteristics of FRCs that drive AFRL's interest are their low dry mass and ability to operate on complex propellants. Due to the high plasma densities present in the discharge, FRCs can be physically smaller than most other propulsion devices operating at similar power levels. Further, because FRCs do not require strong, carefully shaped magnetic fields, there is no massive magnetic circuit as Hall thrusters require. Finally, the high instantaneous powers delivered into the plasma are well-suited to ionization of complex molecules such as those typically used in chemical propulsion. FRCs therefore have the potential to serve as the EP portion of a multi-mode system, albeit likely at reduced efficiency compared to the performance that can be achieved with xenon propellant.

The second technology under consideration for next generation EP is the electrospray, which functions by applying a strong electric fields to extract and accelerate very small (e.g. several microns) droplets of liquid metals or ionic liquids. Because this method does not require ionization of a working fluid, the parasitic energy loss associated with plasma generation is avoided and electrospray efficiencies can be very high, in some cases up to 80%.[15] Designs currently under development utilize modern microfabrication techniques to place hundreds or thousands of emitters on a single, small chip.[16] With further refinement, electrosprays are expected to achieve thrust densities comparable to gridded ion or Hall thrusters. Because of their high performance and operation on ionic liquids, they have the potential to be exceptional performers in a multi-mode system. Operation on AF-M315E has been achieved. Perhaps the greatest challenge in the maturation of electrospray technology is the issue of scaling to high power levels. Because individual emission sites produce thrusts in the nano- or microNewton range, many thousands or perhaps millions of emitters will be required to operate concurrently to achieve useful thrust levels for orbit transfer. While there is no fundamental barrier preventing this from occurring, significant engineering challenges remain to be explored before the full potential of the technology is realized.

CONCLUSION

The In-Space Propulsion Branch of the Air Force Research Laboratory works closely with partners in the Department of Defense and industry to develop technologies to advance the United States' capabilities in the field of spacecraft propulsion. Current programs include technology transition of high-performing, low-toxicity monopropellant thrusters and highly-efficient Hall thrusters to routine use. Ongoing development efforts seek to develop future electric propulsion devices capable of achieving low dry mass and high efficiency while operating on the chemical propellants required in order to achieve flexible, multi-mode propulsion.

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THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

AFRL In-Space Propulsion Program

AAS-15-052

2 February 2015

Dr. Brian Beal, AFRL/RQRS
Program Manager, In-Space Propulsion
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Topics

- Introduction to Air Force Research Laboratory (AFRL)
  - Who we are and what we do
- Air Force in-space propulsion development goals
  - How we define our formal technology development goals
  - Current goals in electric propulsion
- Electric Propulsion technologies
  - Hall thrusters
  - Field Reversed Configurations (FRCs)
  - Electrosprays

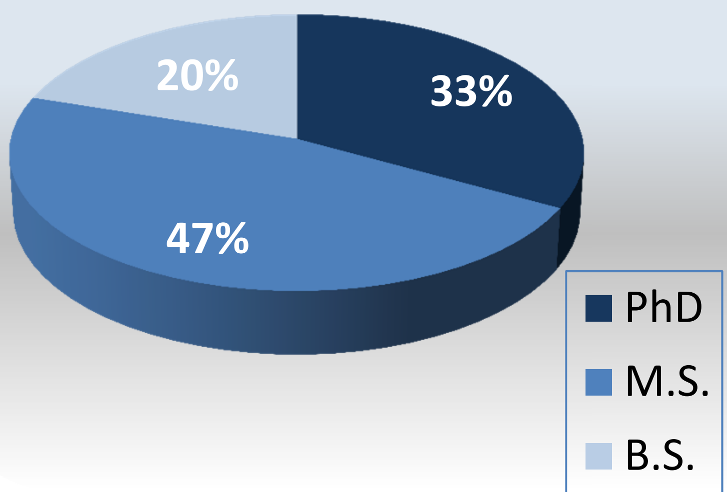
Introduction to AFRL

AFRL Mission:

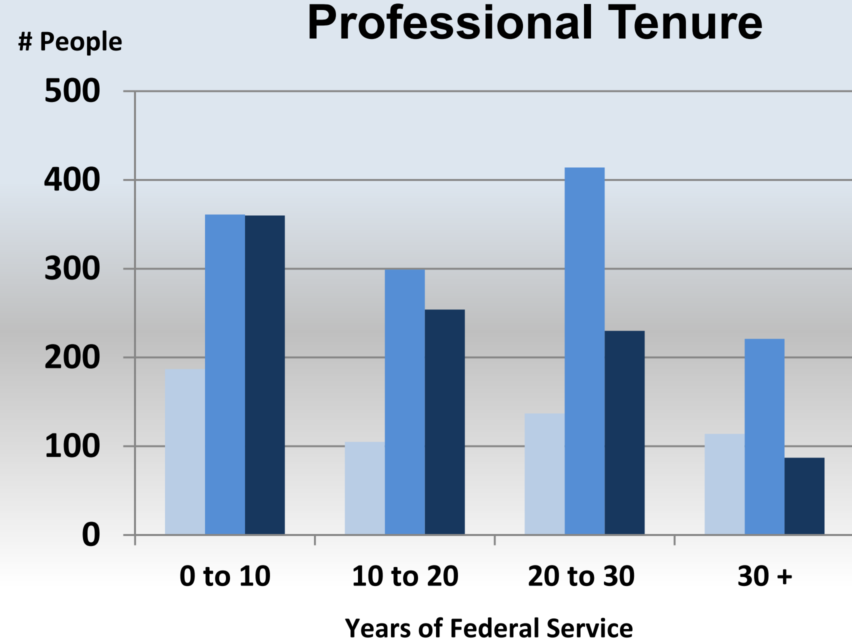
Leading the discovery, development, and integration of affordable warfighting technologies for our air, space and cyberspace force

	Employees	Civilian *	Military	Contractor
Total	10,000	4,651	1,340	4,009
S&Es	6,179	2,774	746	2,659

S&E Education

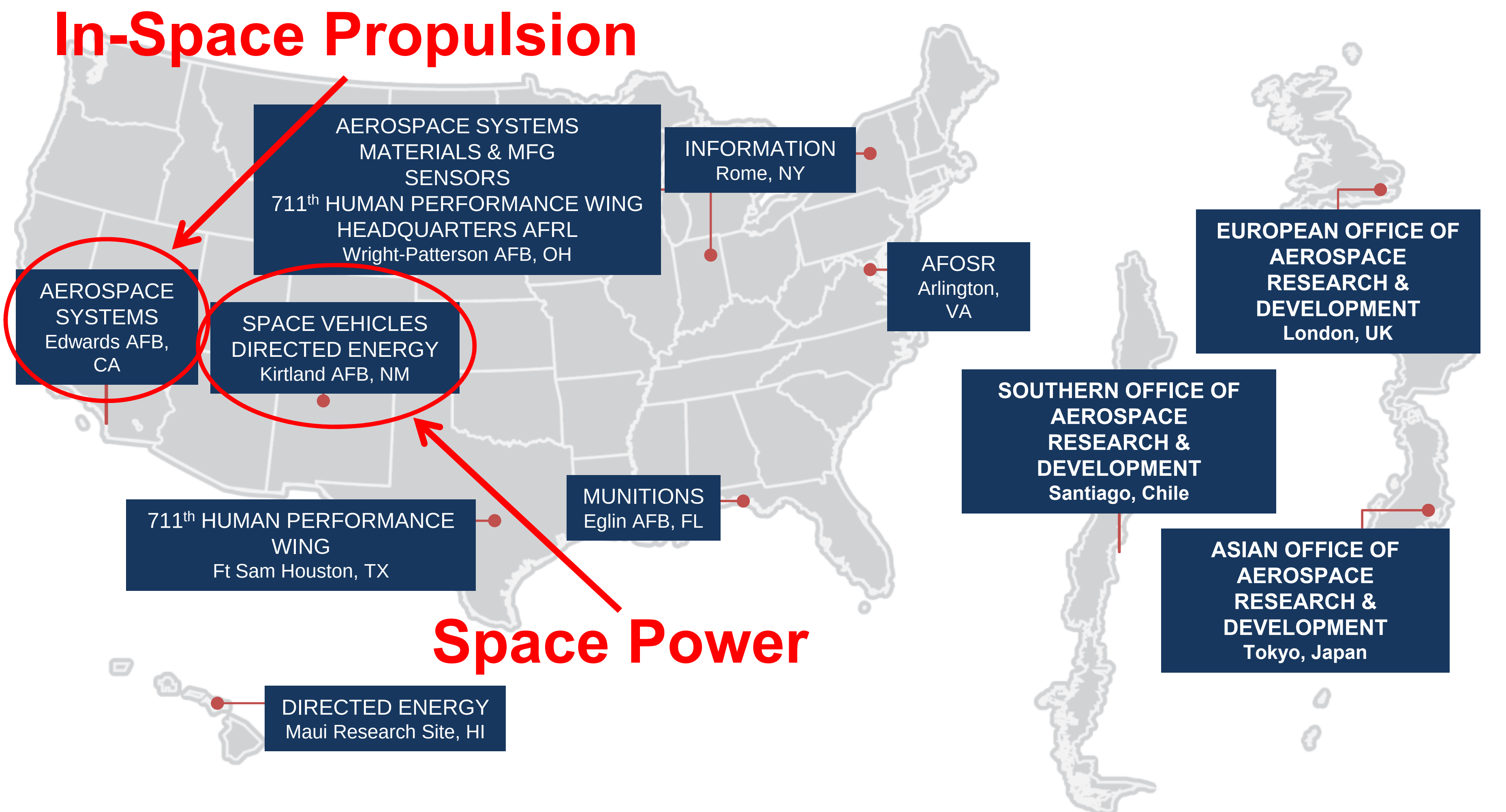


Professional Tenure



* Does not include Students
* Data as of: 31 August 2013

AFRL Locations

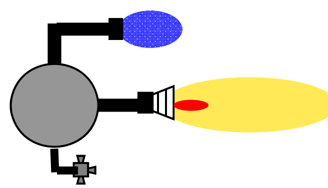


AFRL In-Space Propulsion Branch

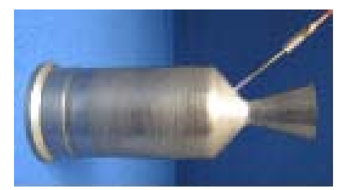
- **AFRL/RQRS has primary responsibility for AF and DoD spacecraft propulsion research and development – basic research (6.1) to advanced development (6.3)**
  - **Primary customer is AF Space Command**
  - **Focus on tech transition and DoD customer support**
- **Modest resources requires leveraging partnerships with other government agencies**
  - **16 civil servants, 3 military**
  - **$2-3M annual budget (incl. ~15 on-site contractors)**

Electric Propulsion

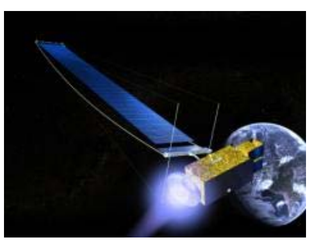
Multi Mode Propulsion



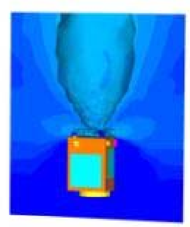
Adv. Chem. Propulsion



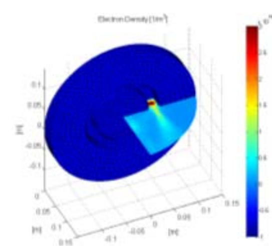
Flight Experiments



Plume Phenomenology



Modeling & Simulation



AFRL Technology Goal Development

Tech Push

USAF CFSP
SMC Tech Needs


United States Air Force
Space Superiority
Core Function Master Plan
FY15

ASD (R&E)
IHPRPT/RP21

AFRL Programs

- Next Gen Chem Prop
- Multi-Mode Propulsion
- Electric Propulsion
- Modeling & Simulation
- Plume Phenomenology
- Micro-Propulsion (CubeSat)

Tech Pull / Sustainment

Programs derived from strategic "tech push" guidance;
Focus on transition and customer support

Technology Push – Capability Improvement

- **Focus on advancing technology in areas that have high impact – trade studies and sensitivity analyses**
  - **Which parameters should we push on?**

- **Two fundamental relations capture <u>most</u> of the big picture:**
  - **I_{sp} and thrust are fundamentally linked by conservation of energy**

$$\eta = \frac{gI_{sp}}{2}\left(T/P\right)$$

η = efficiency

I_{sp} = specific impulse (s)

T/P = Thrust/power (N/W)

  - **Delivered mass fraction is strong function of power and propulsion system specific power (W/kg), as well as allotted trip time**

$$\frac{m_{pay}}{m_0} = \frac{\left(gI_{sp}\right)^2 + 2\eta\alpha\Delta t}{2\eta\alpha\Delta t \exp\left(\frac{\Delta V}{gI_{sp}}\right)} - \frac{\left(gI_{sp}\right)^2}{2\eta\alpha\Delta t}$$

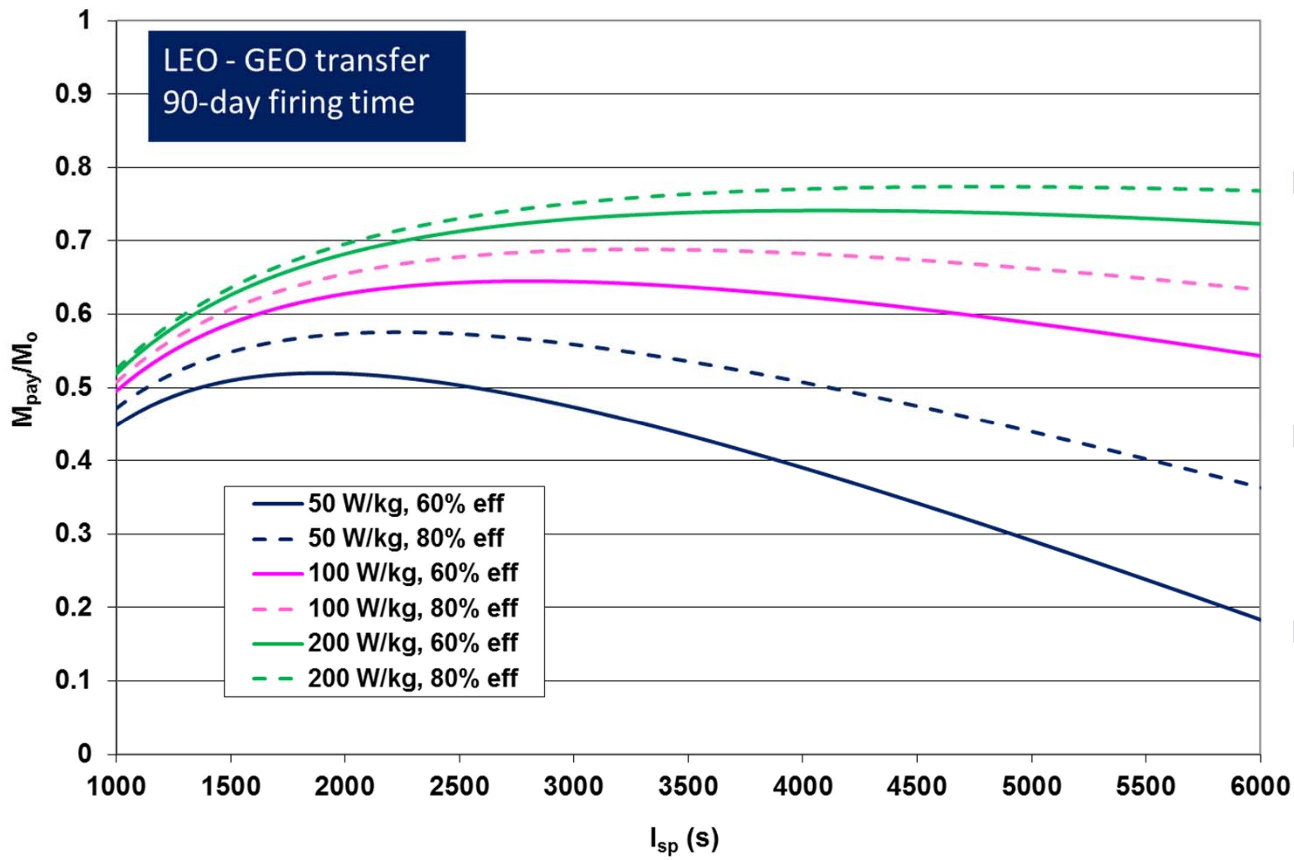
α = Power and prop specific power (W/kg)

Δt = Allotted trip time

ΔV = Velocity increment for orbit change

m_{pay}/m_o = Delivered mass fraction

Example: LEO-GEO transfer



- **Assumes power level can be set to optimum value (idealized)**
- **Increasing α has largest effect on delivered mass**
- **Increasing EP efficiency helps**
- **Optimum Isp is 1500-2000 sec for α=50 W/kg**
  - **50 W/kg is approx SOTA for rigid arrays and Hall thrusters**

RP21 Goals

Boost and Orbit Transfer Propulsion	2017	2027
• Reduce Stage Failure Rate* (RP)	75%	75%
• Improve Mass Fraction (Solid)	18%	38%
• Increase ISP % (Solid/Liquid* (RP))	2%/0%	5%/4%
• Increase Thrust to Weight % (Liquid, (RP))	103%	103%
• Reduce Engine Turn Time(Reusable)	<8hrs	<4hrs
• MTBO/MTBR (Missions, Liquid)	50/100	50/100
• Decrease Motor Health State Uncertainty	20%	50%
Spacecraft Propulsion		
• Increase Efficiency (ET/ES/EM)	15%/15%/10%	65%35%/30%
• Decrease EP System Dry Mass (ET/ES/EM)	0%/50%/50%	75%/90%/90%
• Decrease Flexible Prop.System Wet Mass	35%	65%
• Increase Chemical Prop. Density Isp	5%	15%
• Decrease Chemical Prop. Dry Mass	10%	40%
Tactical Propulsion*		
• Increase Total Impulse (RS&Smokey/MS)	20%/33%	35%/45%
• 4 Pulse motors		
• RS/Smokey Total Impulse Penalty	10/Mf	0
• Minimum Smoke Increase Total Impulse	5%	25%
• Increase Density Isp	5%	7%
• Insensitive Munitions*	See JIMTP & Backup Information	

* Additional Backup goal information exists

Specific Technologies of Interest

Hall thrusters

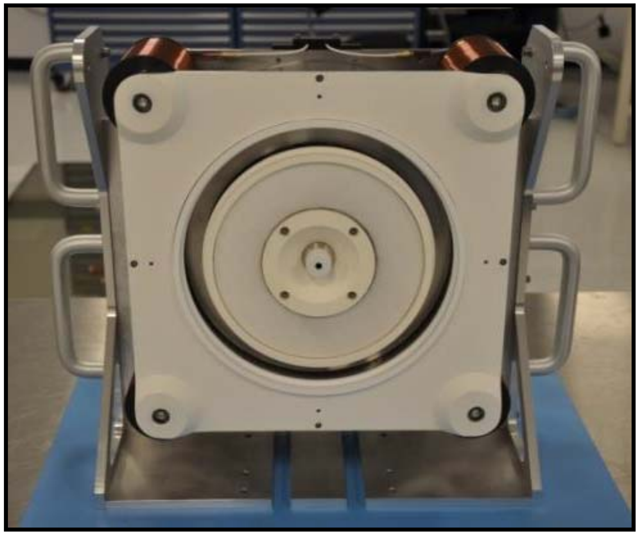
- Hall thrusters represent bulk of AFRL electric propulsion work over last ~15 years
  - Extensive experience with thruster design, build, ground test, and flight
  - Hall thrusters are baseline against which we assess new technologies
    - Aerojet XR-5 (BPT-4000) and Busek BHT-200 are examples of current SOTA
    - Efficiency: 55-60%, α~180 W/kg (~5.5 kg/kW)

- Recent Hall thruster work
  - HPPS performance improvement program – thruster and modular PPU
  - H6 In-House Hall thruster testbed
  - Alternative propellant SBIRs (bismuth and iodine)
  - Concentric channel Hall thrusters

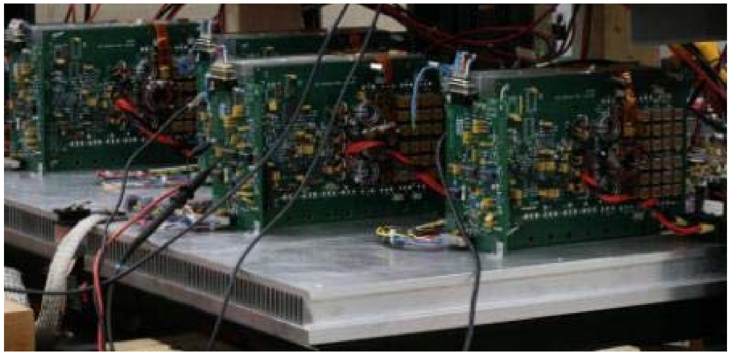
- AFRL now assesses Hall thrusters to be mature technology
  - Note: “Mature” means ready for routine use on high-priority national security spacecraft; “mature” DOES NOT mean there’s no more useful work to do – jet engine analogy
  - Remaining AFRL work on Hall thrusters is largely focused on technology sustainment and transition support, not fundamental development

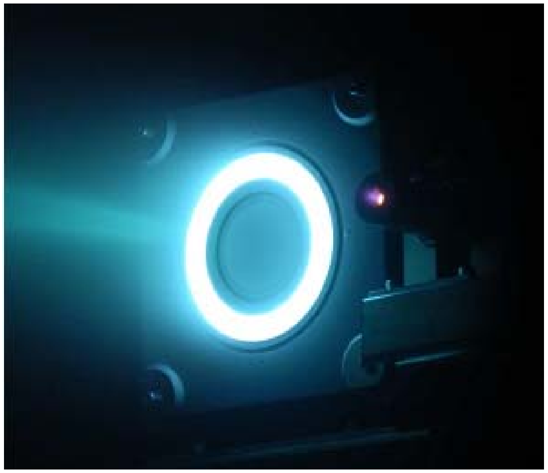
HPPS Hall Thruster Program

- High Power Propulsion System (HPPS) program goals
  - Expand Isp operating range (1000-3000 sec)
  - Improve system efficiency
  - Demo ability to scale in power



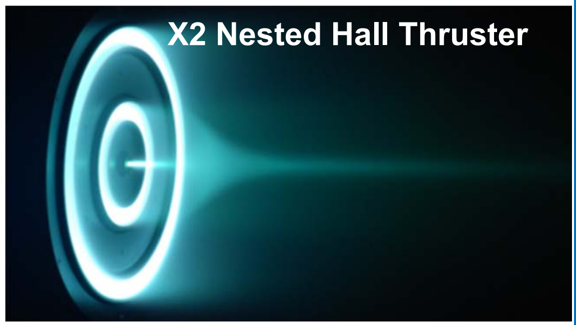
- Demo'd power density effects & performance across I_{sp} range
- Modular PPU & control scheme allows operation from 125-800 VDC, variable input
  - Collaboration with JPL and Aerojet





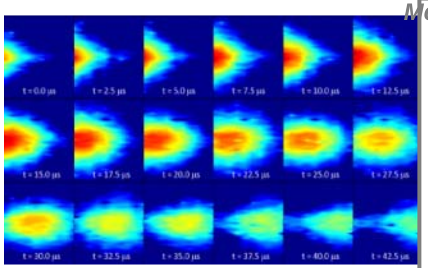
Other Recent Hall Thruster Work

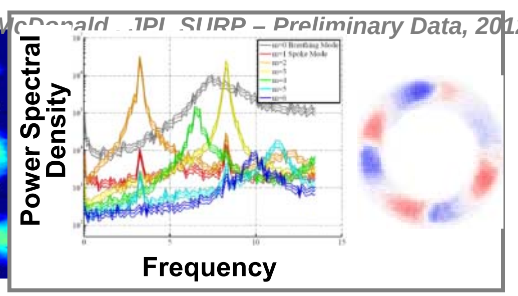
- Nested Hall thrusters
  - Improved packaging for wide-throttling



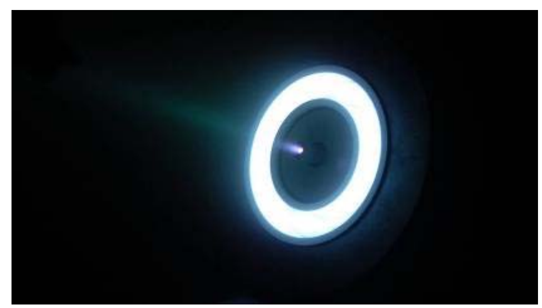
- Alternative propellant thrusters
  - Bismuth and iodine thrusters for compact systems & niche missions

- High-speed plume diagnostics
  - Unique tools for studying physics of time-dependent phenomena





- H6 Hall thruster
  - In-house testbed for parametric performance and plume studies

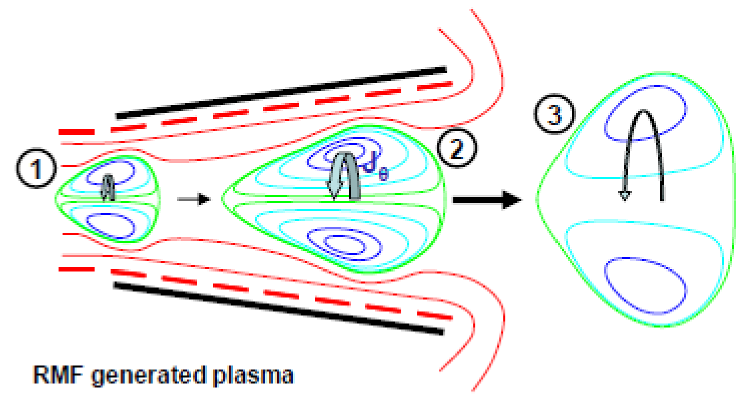


Hall thruster technology developed & available for use

Field Reverse Configuration

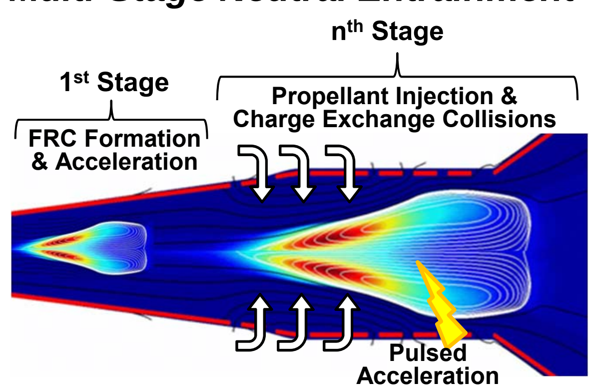
- Field Reverse Configuration (FRC) is offshoot of fusion research
  - Ionization by rotating B-field
  - Pulsed inductive jxB acceleration
  - Magnetically insulated, plasmoid accelerated downstream

- Key attributes
  - Very low mass (estimate ~1-2 kg/kW)
  - Efficiency comparable to or higher than Hall thrusters (predicted)
  - Operates on diverse propellants; suitable for multi-mode applications
  - Neutral entrainment stage enables increased T/P at low Isp
  - Pulsed operation provides near-constant efficiency over wide power range



$$F_z = j_\theta \times B_r$$

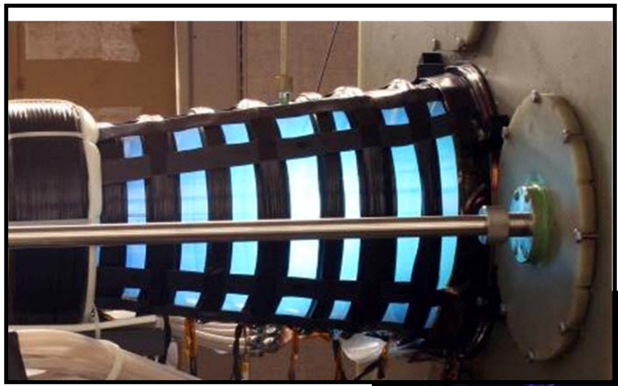
Multi-Stage Neutral Entrainment

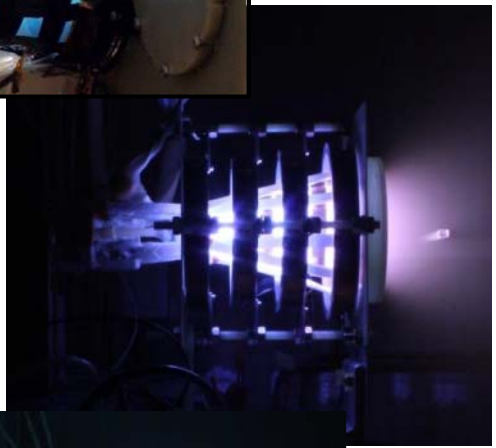


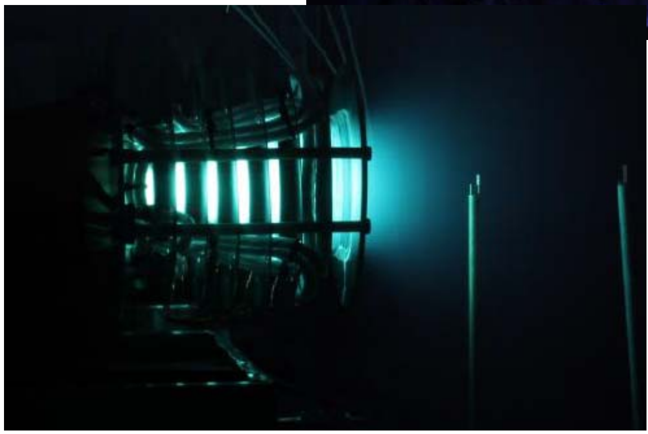
FRC Status

- Pursuing via coordinated SBIRs
  - AFRL, DARPA, NASA JPL

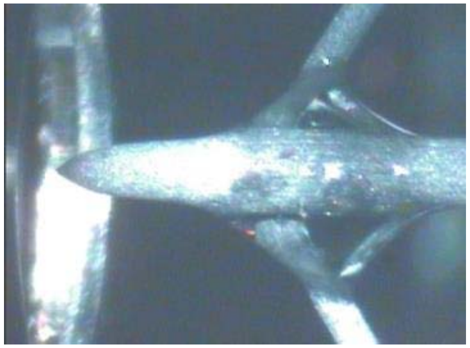
- Technology maturing
  - Operating ~5-kW unit
  - Progressed to in-vacuum operation
    - Expected number of growing pains – no major problems
  - Brassboard PPU functional
  - Recent test of pre-ionizer in AFRL facilities
  - Expecting performance test of full thruster on Xe in early 2015
  - Testing with complex propellants to follow

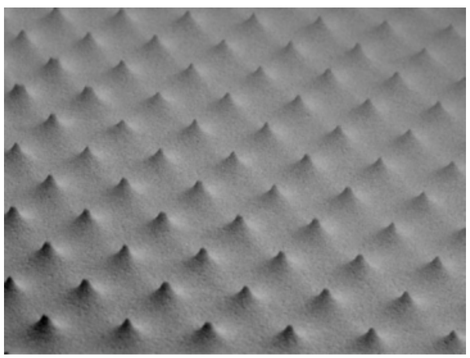


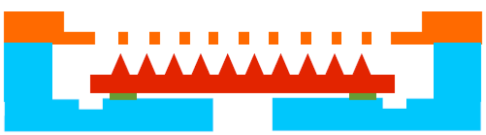




Electrosprays







- Electrosprays function by accelerating ions or charged droplets extracted from Taylor cones
- Key attributes
  - Operate using liquid metals or ionic liquids
    - Suitable for multi-mode using ionic liquid monopropellants
  - Potential to be VERY efficient (>80% possible)
    - Fundamental parasitic loss is overcoming surface tension rather than ionization
  - Potential to be scaled in power – challenge and opportunity
    - Physics happen on micron scales – no fundamental barrier to building electrosprays at multi-kW level, but much development required
    - Manufacturing and robust system design are critical
- AFRL has high interest, but limited investment for now
  - Previous effort showed feasibility to electrospray AF-M315E
  - Incremental progress through SBIRs
  - AFRL supporting NASA and NRO efforts where possible

Summary & Discussion Topics

- AFRL has active programs in electric propulsion and space power
  - Aerospace Systems and Space Vehicles Directorates collaborate regularly
- Projects focused on satisfying near-term mission pull while meeting technology push goals for performance enhancement
  - Hall thrusters ready for routine use – knowledge base exists to build systems at variety of power levels & operating points
  - FRCs and electrosprays under development for increased efficiency and specific power
    - Making progress despite budget challenges
    - Collaborations across mission partners (NASA, DARPA, etc.) are essential
- Routine flight experiments provide important validation data and enhance technology transition