Overview of the Joint AdvaNced PropUlsion InStitute (JANUS)

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The Joint AdvaNced PropUlsion InStitute (JANUS) is a NASA-funded endeavor to enable and proliferate the flight of high-power electric propulsion (EP) systems. Successful completion of this 5-year effort will establish physics-based limits, mitigation techniques, and extrapolation procedures to provide a probabilistic assessment of the in-space performance and lifetime of high-power (~100 kW) EP devices. The assessment will come from measurements made in ground-based test facilities combined with predictive engineering models. To realize this vision requires a significant advance in the understanding of the limitations of test facilities, physics-based numerical models, mitigation technique efficacy, and in-space operation of EP devices. To do so, JANUS addresses four interdependent research pillars: (1) Thruster Testing, (2) Facility Fidelity, (3) Diagnostics and Fundamental Studies, and (4) Physics-based Modeling and Integration. JANUS uses uncertainty quantification and sensitivity analysis for each pillar of all performance and life models. Specifically, the work focuses on HETs and GITs operating on xenon and krypton gases. This effort will deliver several new tools, strategies, and guidelines for evaluating existing infrastructure and designing new infrastructure for testing high-power EP. To achieve this, JANUS has mobilized a team of researchers who are subject-matter experts in the relevant research areas. The home institutions of the principal participants are Georgia Institute of Technology, University of Michigan, University of California, Los Angeles, University of Illinois, Colorado State University, University of Colorado, Stanford University, and Western Michigan University. JANUS collaborates with government and industry partners to incorporate the advancements into present and future research and development processes.

I. Introduction

Presently, the state-of-the-art approaches to correlate ground-test results to in-flight performance and wear are insufficient for the operation of high-power electric propulsion (EP) devices (> 100 kW). This stems from ground-based EP test facilities interacting with thruster operation. The resultant ground-based thruster operation does not represent in-space performance or lifetime. These facility effects include elevated pressure from residual, inadequately pumped gas in the test facility, contaminants from the facility interacting with the thruster, and uncertain electrical paths through the thruster plume and the test facility walls. Over the past 40 years, facilities, test methodologies, and numerical models have been established for EP devices approaching 20 kW, mostly Hall effect thrusters (HETs) and gridded ion thrusters (GITs). However, the existing test facility infrastructure and tools are not directly extensible to high-power devices (~100 kW). High-power EP technology cannot be realized without improving our testing and modeling capabilities. There are gaps in the understanding of these facility effects that will require the combined expertise of a variety of experts to identify and model. Therefore, the establishment of such physics-based understanding, along with appropriate models, is imperative to the development of future high-power electric propulsion systems.

To improve current testing and modeling capabilities for high-power EP, existing knowledge gaps in four categories should be addressed: (1) Thruster performance is perturbed by facility pressure effects. The elevated facility background pressure and the resultant increase in neutrals lead to increases in gas ingestion by the thruster, charge-exchange ions production, and plume divergence that collectively reduce confidence in the prediction of performance in space. Absolute standards for a sufficiently low background pressure to ensure ground tests reliably correlate to in-space performance do not exist. (2) Thruster lifetime is masked by facility contamination. The high-energy particle flux to the facility walls increases rates of backsputtering. Test facilities are lined with graphite to minimize this effect, but experiments still show deposition, layering, flaking, and spalling of films deposited on thruster and facility surfaces. The net effect of contaminant coating of the thruster is reduced confidence in predictions of thruster lifetime. (3) The large volume of dense, conductive plasma expelled from the thruster electrically couples it to the test facility. The effects of this interaction include low resistance paths between thruster surfaces and the test facility, modified electron mobility, and facility-enhanced beam neutralization. These processes only occur in the ground-test facility, thus reducing confidence in predictions of stability and performance. (4) Only disparate, limited spatial and temporal models exist for EP devices, plumes, and sputtering. The models must be integrated and, furthermore must include the impact of uncertainty in experiment and model fidelity as well as be rigorously verified and validated.

The goal of the Joint AdvaNced PropUlsion InStitute (JANUS) is to enable and proliferate the flight of high-power EP systems. Successful completion of the proposed studies will establish physics-based limits, mitigation techniques, and extrapolation procedures to provide a probabilistic assessment of the in-space performance and lifetime of high-power (~100 kW) EP devices.

JANUS addresses the challenge of predicting the performance and life of high-power EP devices in-space through a fully integrated research program with four interdependent research pillars: (1) Thruster Testing, (2) Facility Fidelity, (3) Diagnostics and Fundamental Studies, and (4) Physics-based Modeling and Integration. The effort will focus on HETs and GITs operating on xenon and krypton gases. The methodologies and models will be extensible to other EP devices, including magnetoplasma dynamic thrusters (MPDTs) and field-reversed configurations (FRCs). The extension of the modeling, mitigation techniques, and standards to high-power testing will require the combined efforts of all four pillars. To ensure efficient integration of these efforts and achieve practical results in the five-year timeline, JANUS will use uncertainty quantification (UQ) and sensitivity of the overall thruster performance and life models to drive and accelerate the modeling and experimental inquiries. Unexplained physics and unknown properties will be treated as sources of uncertainty in the performance and life models that impact confidence in the predictions. Thus, the UQ and sensitivity analyses will accelerate the research by focusing the efforts of the team on processes that require higher-fidelity simulations and more in-depth targeted experimental investigations to update models and reduce the uncertainties in predictions. We leverage this insight to develop mitigation strategies to compensate for these effects via modeling and experiments. Systematic evaluation of these mitigation strategies will lead to new standardized tools, techniques, and ground-testing methodologies to achieve the ultimate goal of extending the results of high-power ground tests to in-space operation. This innovative research integration plan will produce research efforts, tools, and databases that represent a huge return on investment and were not conceived in the past because of insular, disjointed investigations.

This paper overviews the JANUS project by detailing the research pillars, structure, different expert responsibilities, and the various activities that will take place.

II. Research Pillars

JANUS is composed of 16 faculty members from eight universities, Georgia Institute of Technology (GT), University of Michigan (UM), University of California, Los Angeles (UCLA), University of Illinois (UIUC), Colorado State University (CSU), University of Colorado - Boulder (UCB), Stanford University (SU), and Western Michigan University (WMU). JANUS contains three additional faculty collaborators from three minority-serving institutions (MSIs) Clark Atlanta University (CAU), Chicago State U., City Colleges of Chicago (CCC). In addition, JANUS formally interacts with three leading organizations (Busek, Aerojet Rocketdyne, Aerospace Corporation, Lockheed Martin, and Orbion) in EP. Figure 1 presents the JANUS organization chart. The structure will be used to coordinate, guide, and nurture the interactions of this diverse group of experts. The work and interactions within the structure of JANUS will ensure a highly interdependent, multidisciplinary approach to all portions of the research plan to develop unified experimental approaches and complementary models for accurate prediction of thruster performance and lifetime. To ensure the integration and interdependence of JANUS, the modeling and the experimental teams work closely together to determine and execute synergistic campaigns.

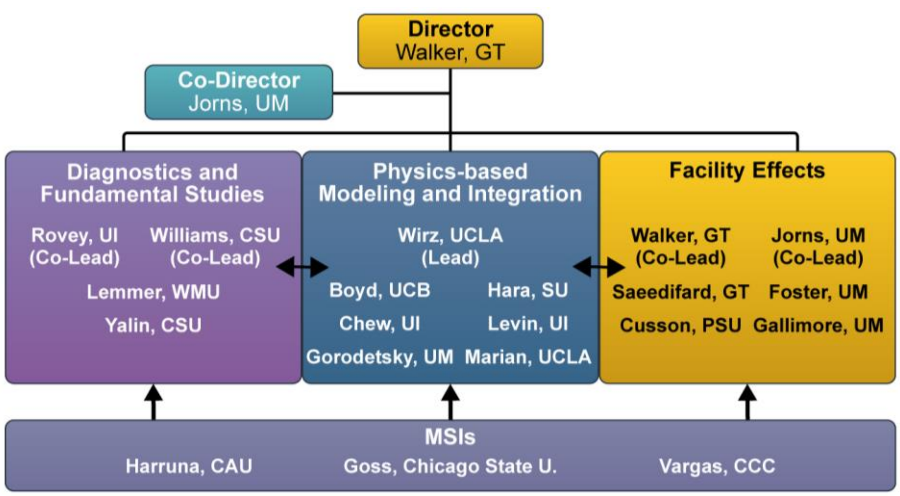

Figure 1 Organization of JANUS

A. Facility Effects

This pillar addresses the pressure and electrical facility effects. The goals of pressure effects-related investigation are to (1) perform experiments on thrusters in a SOA vacuum facility to generate data for model validation, and (2) demonstrate new strategies and methodologies for translating high-power (>15 kW) ground-test data to in-space operation. Key measurements will include performance, high-speed fluctuations in internal and near-field plasma, and neutral flow properties. This effort will leverage the UM Large Vacuum Test Facility (LVTF), its suite of diagnostics and thrusters, and a set of new diagnostic capabilities.

The focus of the electrical effects work is to perform experiments on facility design and EP electrical coupling in a SOA vacuum facility at moderate powers (<15 kW). The results will serve as a source of data for model validation of facility effects. The effort will include power processing, facility modification schemes, new diagnostic development, and evaluation of facility performance extensions by throttling pumping speed with low-power EP. This effort leverages the low operating cost and high pumping speed of Georgia Tech (GT) Vacuum Test Facility 2 (VTF-2).

B. Diagnostics and Fundamental Studies

The focus of this pillar is to elucidate unexplored aspects of thruster-facility interactions. The effort will develop and employ new diagnostics with well-characterized uncertainty in high-power thruster tests and conduct fundamental plasma-material interaction studies on surfaces with flight features. The measurements will enhance our understanding of the facility far- and near-field pressure effects, contamination, and electrical coupling. The fundamental studies will focus on the low-energy regime of ion sputtering of materials, and they will characterize the carbon deposition processes using a novel carbon isotope tracking technique.

C. Physics-based Modeling and Integration

The focus of this pillar is to develop multi-fidelity/multi-physics computational, analytical, empirical, and theoretical models and coordinate them with experiments to provide a means to predict thruster performance and life in space. The results will also be used to improve EP ground testing and facilities. The effort will *leverage SOA models* that are directly applicable and extensible to JANUS objectives, as well as add new physical processes to existing models. UQ and probabilistic risk and mitigation will determine and guide modeling and experimental efforts and ensure the interdependence of all modeling and experimental work within JANUS. Additionally, the effort will be indelibly coordinated with experimental efforts to ensure that essential data is obtained for model verification and validation (V&V).

III. Approach

A. State of the Art Research and Practice

<u>Ground testing of high-power EP devices</u>

Three broad characteristics are evaluated when developing new devices: performance (*e.g.*, thrust, efficiency, stability), lifetime, and spacecraft-thruster interaction. The goal of qualification efforts is to verify that each of these properties satisfies the requirements for the targeted mission. It is standard practice to perform most of this verification through direct testing. In recognition of the expanding required lifetimes for EP missions and increases in discharge power, part of the qualification can now be complemented with analysis [1, 2].

There is a risk that the results of ground tests will not be representative of in-space operation. Previous efforts have focused on establishing standards and methodologies for the ground test environment to help mitigate this risk [3]. Using these standards, we show in

Table 1 the qualitative rankings of our confidence in the ability of the key measurements of the thruster to be representative of in-space operation. These assessments are based on the standards that have been adopted to date for testing and the capabilities of the most highly-capable facilities (assuming a ~700 kl/s-Xe pumping speed).

Table 1 Assessment of confidence in ground tests. Green: validated methods and procedures. Yellow: research and methods have been demonstrated or investigated. Red: missing capability.

	Gridded Ion thrusters			Hall thrusters			Advanced concepts (MPDT/FRC)
Power level (kW)	< 2.3	2.3-6.9	>6.9	≤ 1.35	1.5-13	>13	>20 kW
Performance							
Lifetime							
Spacecraft/EP interaction							

For both low-power HETs and GITs, we have a high degree of confidence in ground tests. This is because the technologies have been developed, qualified, and flown operationally. Correspondingly, several techniques and standards for best practices in testing exist. In contrast, recent work shows that the standards adopted for low-power testing may not apply for the moderate power regime for GITs and HETs [4]. There is less confidence that ground tests will be representative of space. For high-power devices—Hall, ion, and advanced concepts—current ground test methodologies may not yield results representative of in-space operation.

State-of-the-art methods for improving ground testing fidelity at higher power

Multiple strategies have been adopted in the past 40 years to improve testing fidelity as EP power has increased. Absent a full understanding of the impact of facility effects; little emphasis has been placed on mitigation. Our philosophy is to implement engineering solutions to the facility to reduce the source of facility effects. Notable examples include adding pumping capacity, adding low sputtering yield liners, and adopting electrical biasing schemes that are more representative of in-space conditions [5]. While these may reduce the sources of facility effects, these methods cannot altogether eliminate them. Indeed, there is only a finite amount of surface area in the chamber available for pumping, and even the exceptionally low sputtering yield of carbon still produces backsputter. These facts suggest that there likely is an inherent lower bound background pressure and facility backsputter that will be achievable for high-power tests. Thus, there may not be a facility design that will ever yield a test environment truly representative of the in-space environment.

Thus, it is necessary to identify strategies and methodologies for extrapolating from ground tests to the in-space environment. This could be done with a fully predictive model of the thruster and facility. However, the challenge with this approach is that EP systems are highly complex, multi-physics, multi-scale systems involving processes ranging from the molecular to continuum fluid flow. In many cases, the governing physics of these processes and interactions remain poorly understood and have precluded the development of predictive codes.

In light of this limitation, it has become common practice for NASA, the AF (EP-TEMPEST), and industry to apply a combined modeling and experimental approach to compensate for facility effects. In this case, poorly understood physical processes are represented in the model as adjustable parameters, and experimental measurements are used to infer the values for these parameters. For example, in lifetime qualification of the NSTAR and NEXT engines, measurements of sputtering yield and beam current were used as model inputs to a sputtering code to argue that carbon backsputter had a negligible contribution to pits-and-grooves erosion [6, 7]. Recently, experimental data has been used to guide model selections for extrapolating performance and plume measurements of a HET to in-space conditions [8, 9, 10, 11]. Figure 2 shows an example of this latter approach [12]. The facility pressure is systematically decreased, and key quantities of interest are measured. This approach establishes an empirical trend with pressure to which a model is then fit and extrapolated to space-like (*i.e.*, 0 facility pressure) conditions. To date, most models have been empirically-driven with proposed models varying in complexity from linear to transcendental functions. While most of these proposed functions yield agreement with datasets over the measured domain, the fact that these models are empirically driven raises concerns about their validity in regimes outside the range of the experimental data. Thus, the problem of model selection is arguably the major technical hurdle for this method and is why the JANUS approach will incorporate experimentally-validated, physics-based modeling to the extent feasible as described in the following sections.

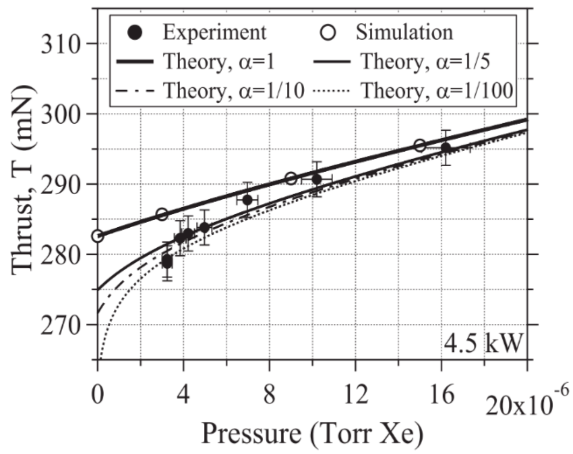

Figure 2   Model fit to experimental data to extrapolate to in-space conditions. NASA JPL [12]

B. JANUS Modeling Framework

Figure 3 illustrates key elements and interrelationships of JANUS. These tiers are categorized into institutional initiatives of Performance and Life Assessment, Thruster Environment Studies, and Fundamental Studies. Since high-power EP facility effects are governed temporally and spatially by multi-scale phenomena, the Fundamental Studies will provide higher fidelity while the Coupled System Studies and Performance and Life Assessment provide greater scope to capture the behavior of the overall system. As described in the following sections, the Fundamental Studies reduce critical uncertainties (*i.e.*, yields, cross-sections, etc.) based on critical physical processes via reduced-order Sub-Models that must be used for the thruster, plume, and environment System Models developed in the Thruster Environment Studies. These coupled System Models comprise the Predictive Engineering Model (PEM) that is used to predict thruster performance and life for test or mission profiles in specified environments (*i.e.*, inside a specified ground facility or spacecraft/in-space environment). The priorities of the efforts within these initiatives are guided by Uncertainty Quantification (UQ).

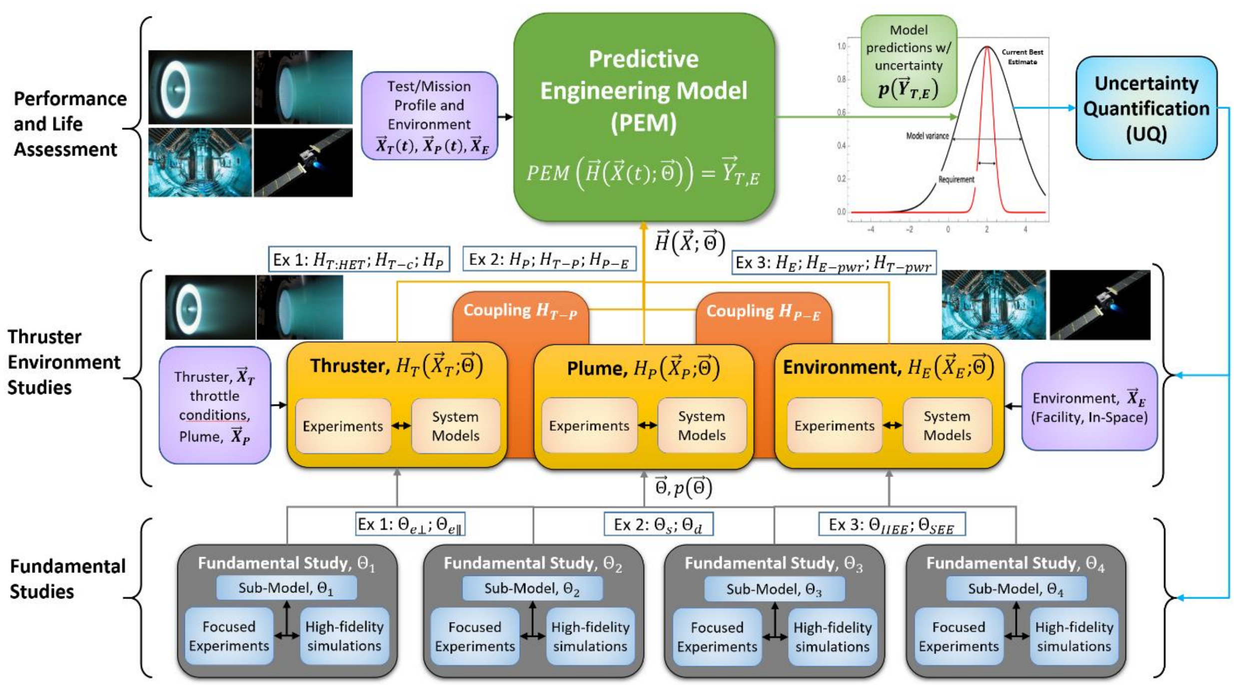

Figure 3   JANUS Modeling Framework. Note: Exemplar Projects (Ex 1, Ex 2, Ex 3) are not defined in this manuscript.

The overall objective of the Modeling Framework is to ensure that the PEM and its associated models will accurately quantify ground-test facility impacts on high-power EP systems. The UQ feedback will systematically ensure JANUS undertakes coordinated efforts that provide the highest payoff towards this objective. By comparing the results between different ground tests and in-space, the PEM can be used to quantitatively assess the ground-test facility designs, methodologies, and procedures that most effectively mitigate facility effects. The following sections describe this framework and the associated models.

C. Predictive Engineering Model (PEM)

The PEM, which we denote as $PEM\left(\vec{H}\left(\vec{X}(t);\vec{\Theta}\right)\right)$, is a function that yields model predictions of the thruster performance and life in a prescribed environment, $\vec{Y}_{T,E}$. Examples of components of $\vec{Y}$ include global parameters such as performance (*e.g.*, thrust, specific impulse, efficiency) and lifetime, as well as spatially distributed properties like the plume profiles, species/contaminant fluxes, and temporal properties such as thruster stability. The function PEM iteratively determines the coupled effects of the thruster, plume, and environment System Models, $\vec{H} = (H_T, H_P, H_E,\ H_{T-P}, H_{P-E})$, where H_{T-P} and H_{P-E} describe the coupling functions between the respective models. Not shown in the figure is electrical power system (*pwr*) coupling, as explained in Exemplar 3, that will inform additional coupling functions H_{pwr-T} and H_{E-pwr} for power system to thruster, and environment to power system, respectively, thus closing the thruster-environment circuit. Inputs to $\vec{H}$ include system parameters, $\vec{X} = \left(\vec{X}_T, \vec{X}_E\right)$ such as thruster life, throttle conditions, and the facility environment, and model parameters, $\vec{\Theta} = (\Theta_1, \Theta_2, \Theta_3, \dots)$ such as sputtering yield coefficients and electron transport diffusion terms. The system parameters are quantities that can be controlled for the thruster, $\vec{X}_T$, *e.g.*, thruster geometry and throttle condition (flow rate, voltage, current, magnetic field setting), as well as the environment, $\vec{X}_E$, *e.g.*, pump location and speed, material liner, and electrical configuration. For in-space operation, $\vec{X}_E$ will describe the orbit environment, spacecraft structure, and surfaces. In the absence of a thruster System Model or in the presence of reliable plume data, one may use detailed descriptions of the plume produced by the thruster, $\vec{X}_P$, as measured via ground-test plume measurements in addition to or in place of thruster inputs. This allows the PEM to estimate the performance of less-developed thruster technologies, such as MPDTs and FRCs, without detailed thruster models. The model parameters, $\vec{\Theta}$, and their use and characterization in the context of the Modeling Framework are described in the Exemplar Projects.

As shown in Figure 4, the PEM takes a test or mission profile, $\vec{X}_T(t), \vec{X}_P(t)$, and the operational environment, $\vec{X}_E$, and iterates through the profile to determine a time history of thruster performance. For each time step, the PEM determines the temporal evolution of life mechanisms and uses a life metric assessment to determine if the thruster has reached end-of-life (EOL) during that time step. **Error! Reference source not found.** uses the example of grid erosion of an ion thruster as the life mechanism and electron backstreaming (EBS) limit as the life metric assessment to determine EOL conditions [1316]. For the PEM to develop a probabilistic distribution for a mission, it will also iterate on key conditional probability distributions for system model inputs, such as model parameters related to key physical processes, $\vec{\Theta}$, and irreducible sources, indicated by $\vec{\gamma}$.

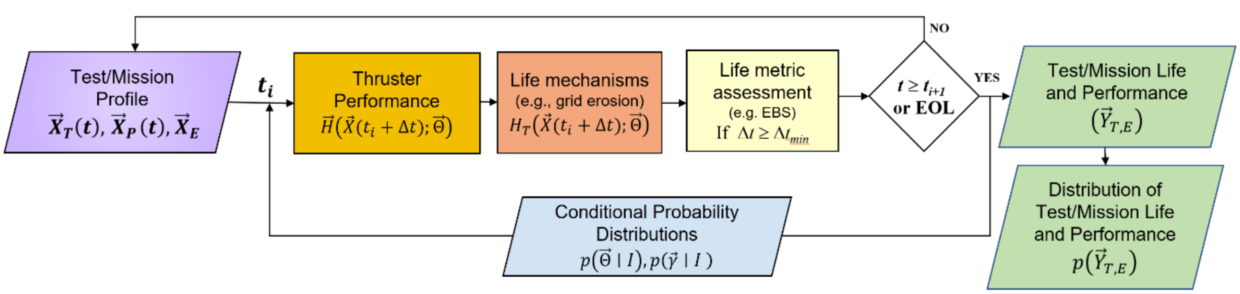

Figure 4 Predictive Engineering Model's iterative framework.

D. Uncertainty Quantification and Optimal Experiment and Model Design

The UQ framework is responsible for analyzing and providing feedback based on results from the PEM and the feedback that can be associated with the contributing System Models and Sub-Models. Specifically, the primary role of UQ is to use the PEM to develop probabilistic extrapolations of thruster performance in space for a specific set of thruster and facility configurations. The UQ approach will also provide feedback to the PEM by identifying sources of uncertainty that contribute to the greatest variability in predictions and suggesting new investigations to gain information. By exercising this feedback loop, we will target the refinement of the PEM towards the goal of improved-confidence predictions.

Armed with $PEM\left(\vec{H}\left(\vec{X}(t);\vec{\Theta}\right)\right)$, we can generate predictions of thruster performance and life for combinations of design and model parameters. The goal is to find predictions for key operating conditions of the thruster, $\vec{Y}_{T,E}$, given an operating profile, $\vec{X}_T(t)$, and environmental configuration, $\vec{X}_E$,. For simplicity, we can assume that the thruster's plume is determined from the thruster condition and environment, *e.g.*, $(\vec{X}_P\left(\vec{X}_T(t),\vec{X}_E\right)$ such that the prediction for the thruster performance and life is $PEM\left(\vec{H}\left(\vec{X}_T(t)\,,\vec{X}_E;\vec{\Theta}\right)\right)=\vec{Y}_{T,E}$. Because there is uncertainty in the model parameters, $\vec{\Theta}$, the PEM model predictions will have uncertainty. Additional uncertainty may also stem from irreducible sources related to the environment, γ_1, manufacturing tolerances, γ_2, and the like, that can be represented collectively by $\vec{\gamma}=(\gamma_1,\gamma_2,\dots)$. The uncertainties in these parameters are expressed as prior distributions $p(\vec{\gamma}\mid I)$ and $p\left(\vec{\Theta}\mid I\right)$, where I denotes the information available at the time of analysis (incorporates all prior available data). The uncertainty in these model parameters directly impacts the confidence of the model predictions from the PEM. The prior predictive distribution is marginalized over the model parameter prior distributions.

The prior predictive distribution can be leveraged to yield probabilistic predictions for the in-space environment. This is the black line in the upper right-hand corner of Figure 3. The largest point represents the most probable predicted state while the width is a direct consequence of inherent model uncertainty. Given our imperfect knowledge of the models for how thrusters respond to facility effects, the uncertainty in the predictions will be larger than a mission-level requirement (the red distribution in Figure 3). One of the overarching goals of JANUS is to reduce this uncertainty. Improving PEM Model confidence can be accomplished in two ways. The *first method* (system-level), second tier of Figure 3, is based on performing dedicated fundamental studies to narrow the prior model parameter distributions, $p\left(\vec{\Theta}\mid I\right)$. Figure 5a shows an example of this for a sub-model for the sputtering yield for xenon impacting on Al. We start with a wide marginalized probability distribution for one of the model parameters for the sputtering data. Targeted experiments and detailed studies are used to improve confidence in the model parameters in strategic regions of interest. This process yields a narrower distribution and a more confident prediction by the overall PEM.

The *second method* (fundamental studies), bottom tier of Figure 3 and Figure 6a, is to perform studies of the thruster at its design state, $\vec{X}_T(t)$, while we vary the facility environment to *n* set points, $\vec{X}_{E(i)}$ (*e.g.*, pumping speed or electrical boundary condition), and measure the thruster operation at these states, $\vec{Y}_{E(i)}$. This generates a dataset of new information, $\vec{D}=\{\,(\vec{X}_{E(1)},Y_{E(1)}),(\vec{X}_{E(2)},Y_{E(2)}),\dots,(\vec{X}_{E(n)},Y_{E(n)})\}$. We then can apply Bayesian inference to generate a **posterior probability distribution function,** $p(\,\vec{Y}_{T,E}|\vec{D})=\int p\left(\left(\,\vec{Y}_{T,E}\,|PEM,\vec{\Theta},\vec{\gamma}\right)p\left(\vec{\Theta}\mid\vec{D}\right)p\left(\vec{\gamma}\mid\vec{D}\,\right)d\vec{\Theta}d\vec{\gamma}\right.$, where $p\left(\vec{\Theta}\mid\vec{D}\right)$ denotes the posterior distribution of model parameters inferred from the dataset. The posterior probability distribution yields an updated prediction for the model output that has been informed by new, system-level data. This distribution is then sampled (Figure 6) to yield a median prediction (denoted as a black line) and confidence intervals (denoted as dashed lines) as a function of the facility environment. Fundamentally, this approach can be thought of as a form of multi-dimensional regression where we have rigorously accounted for sources of uncertainty in evaluating the "goodness of fit."

For both approaches to improve PEM uncertainty, it will be necessary to perform time-intensive experiments and simulations. We will use the UQ results to provide feedback to the System Models to quantitatively determine the model parameters, Θ_i, that contribute the greatest uncertainty to the results of the PEM. The JANUS team will coordinate efforts and resources within the pillars to focus on the sub-model uncertainties that are the dominant contributors to PEM uncertainty.

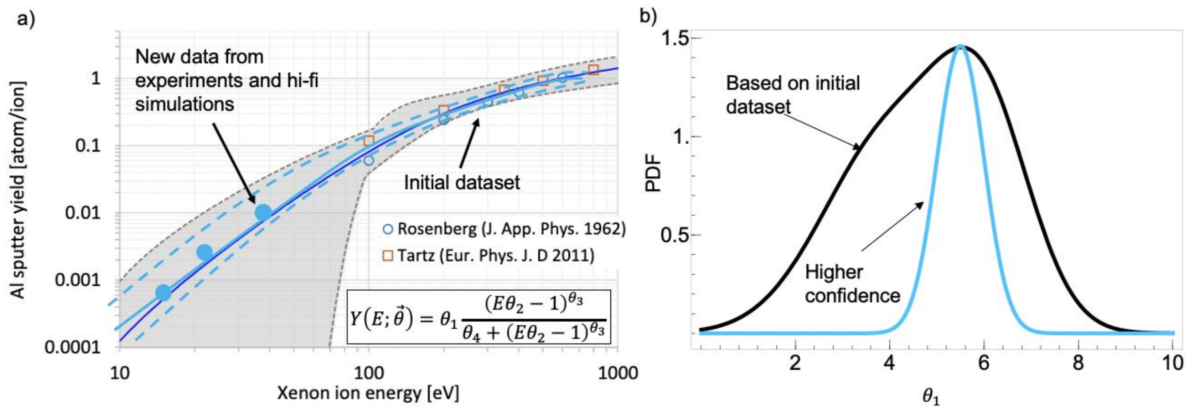

Figure 5 Fundamental studies applied to reduce uncertainty in sub-model parameters. a) Sputtering yield data [17] for xenon on aluminum. The best fit line is a sub-model based on the Eckstein formula. Model confidence denoted by dashed lines. b) Marginal probability distribution for one of the model parameters before and after additional data is collected.

Simple sampling-based UQ methods will not work because generating priors and posteriors can require 10,000s of runs of the underlying PEM to converge. In our case, some of our constituent models, such as HPHall, may require hours to converge. Instead, Co-I Gorodetsky has developed a cohesive multifidelity UQ setting in the context of both sampling and surrogate methodology [18, 20] to yield accurate estimates for probability distributions at a fraction of the computation expense. The sampling methods leverage correlations amongst model ensembles and the surrogate methods leverage localized mappings between each model. The UQ effort will leverage the Dakota Framework, a proven tool for multifidelity modeling initiatives. Co-I Gorodetsky works with Dakota developers to add support for these methods and has independent software for performing these analyses within JANUS.

As discussed in the Modeling Framework, the PEM relies on coupled System Models and reduced-order models (*i.e.*, Sub-Models, $\vec{\Theta}$) of physical processes to capture the overall system behavior. V&V of the System Models for exemplar operating conditions is the primary objective of the Thruster Environment Studies so that these models can then be operated iteratively within the PEM model for performance and life predictions. Table 2 shows the SOA models developed and/or used by the PI and Co-Is. We have completed a development need evaluation of many of the models relevant to thruster and facility predictions.

Table 2 State-of-the-art JANUS Models for Facility Effects

Model	System Models, $\vec{H}$, and Sub-Models, $\vec{\Theta}$	JANUS Co-Is with examples of related model experience*
UQ	All	Gorodetsky [18, 19], Jorns, Wirz [21]
HET	$H_{T:HET}$	Hara, Boyd[2226], Jorns[27],Wirz [28]
GIT	$H_{T:GIT}; H_{T-P}$	Wirz [**Error! Bookmark not defined.**], Williams[**Error! Bookmark not defined.**], Boyd [29]
Cathode(c)	$H_{T-P}; H_{T-c}; H_{c-P}$	Hara[30,31,85,93], Boyd, Levin, Jorns[32], Wirz
Plumes	$H_P; H_{T-P}; H_{P-E}$	Levin [33, 34, 35, 36, 37], Boyd, Hara, Wirz
Facility(f)	$H_{E:f}; H_{P-E:f}$	Boyd[85, 93], Levin [35, 38], Wirz,
Spacecraft(sp)	$H_{E:sp}; H_{P-E}$	Levin [39], Boyd, Hara, Wirz [4044]
Electrical (pwr)	$H_E; H_{E-pwr}; H_{T-pwr}$	Saeedifard [45], Walker [8183]
Sputter-Deposition	$\Theta_s; \Theta_d$	Chew [4648], Marian [49], Levin [50], Wirz [5154]
IIEE, SEE	$\Theta_{IIEE}; \Theta_{SEE}$	Marian [55, 56], Levin, Wirz [57, 58, 59]
Electron Transport	$\Theta_{e\perp}; \Theta_{e\parallel}$	Hara [60], Jorns, Wirz, Walker
Collisions	$\Theta_{CEX}; \Theta_{MEX}$	Levin [61], Wirz [6264], Boyd

E. Interdependent Research Objectives enabled by the JANUS PEMs

The PEM framework will be used to accomplish three of the main research objectives (Figure 6). The results of each objective promise to provide breakthroughs within the five-year timeline.

Objective 1: Demonstrate methodologies to make probabilistic assessments of in-space performance and lifetime from measurements made in non-optimal test facilities. We will develop a methodology based on regressing parametrically-generated datasets of thruster operation with the PEM and then extrapolating these regressions (with confidence assessments) to space. To increase confidence in the extrapolations, our efforts will combine physics-based model development, targeted experiments, targeted high-fidelity simulations, and OED.

Objective 2: Define new test standards and requirements for high-power EP testing. We will leverage the validated PEM framework to perform a sensitivity analysis to determine relative thresholds for the facility environment, *e.g.*, the ratio of backsputter rate to erosion rate, below which the predicted properties of the thruster are not expected change (within error) from ground to space.

Objective 3: Develop procedures and techniques for facility design, upgrades, and thruster operation to meet new testing requirements. The facility configuration (pump placement, electrical boundaries, etc.) is an input to the PEM. Thus, we can apply the PEM to explore design space to identify facility configurations that will minimize certain facility effects below the levels identified in Objective 2. This will result in new configurations that will be explored and characterized experimentally. The resulting data will be used to refine the PEM and generate new configurations. To augment this effort, JANUS also will explore novel materials and configurations for reducing known facility effects.

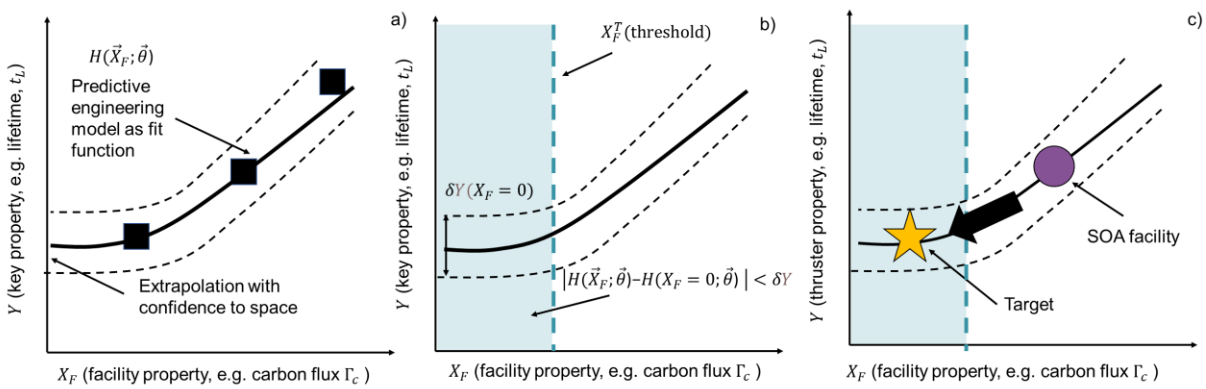

Figure 6 Illustration of leveraging the PEM to achieve the research objectives. a) Regress data generated by varying the facility configuration to extrapolate to space, b) Establish thresholds below which the thruster is no longer sensitive to the facility effect, and c) Identify design strategies and methodologies to modify SOA facilities or building new facilities that mitigate key facility effects.

IV. Research Plan

The research plan mirrors the structure shown in Figure 3 and is based on a bottom-up approach. We start first with fundamental studies related to sub-models and work progressively upward in scope, incorporating the sub-models into higher level system models and finally into the overall PEMs. The overarching goal at each step is to perform a combination of experiments and simulations to reduce model uncertainty. The research plan culminates in the ability to apply the PEM to achieve the key technical objectives. The resulting standards and methodologies that emerge will be documented in a series of technical guidebooks. Because sub-models are built on fundamental physical processes in multiple technologies, they are relevant to PEMs for HETs, GITs, and other thrusters. A general overview description of the major activities of the research plan are listed here, with more specific details provided in three exemplar projects focused on pressure effects, contamination, and electrical coupling.

Identify reduced-fidelity models and sources of epistemic uncertainty for facility-related processes: Examples include an equivalent circuit model for the thruster/facility electrical coupling with unknown circuit elements, algebraic models for the energy dependence of sputtering with free fit parameters, and transport models with unknown diffusion coefficients.

Build and validate novel diagnostics for measuring key physical processes in sub-models: Examples include techniques to measure carbon, neutral, and plasma transport in the plasma plume and methods for differential sputtering measurements at low impact energy.

Implement high-fidelity, kinetic simulations for key physical processes in the sub-models: These tools can be used to supplement or replace diagnostics where the processes may not be experimentally accessible. Examples include PIC models of carbon transport as well as 2D kinetic models of plasma turbulence in the near-field of HETs.

Compare results from targeted experiments and high-fidelity models to determine and reduce model uncertainty in sub-models: Targeted experiments and high-fidelity numerical experiments are performed in parallel to infer probability distributions for the sub-model parameters (Figure 7). Optimal experimental design is employed to guide efforts to reduce uncertainty.

Integrate reduced fidelity models into systems models and revise estimates for model parameter uncertainty by performing dedicated system level experiments: For example, electron transport models will be incorporated into a HET near-field plasma code and used to make predictions for local plasma properties. This task is necessary to capture potential non-linear coupling that may exist in the uncertainties of the different sub-model parameters.

Integrate system models into PEMS and refine model uncertainty with integrated tests: Methods for linking the models and arriving at converged solutions in a time-efficient manner must be explored. OED is leveraged to guide a series of integrated, parametric experiments and high-fidelity numerical simulations to reduce prediction uncertainty (Figure 6a).

Apply PEMs to build methodologies and guidebooks for high-power testing: In this task, the validated PEMs will be leveraged to achieve the interdependent research objectives outlined in **Error! Reference source not found.**. These include developing methodologies for performing extrapolation, mitigation, and establishing new standards for testing (Figure 5). As with Step 6, this task will require a combination of parametric experimental studies, OED, and surrogate-based sampling methods.

F. Exemplar Project 1: Pressure Effects on Performance and Plume Dynamics

The goal of this exemplar project is to develop system-level models ($H_{T:HET}$, H_{T-c}, and H_P from Table 2) for how the HET plasma, cathode, and plume respond to finite neutral pressure in the facility. The model will guide the establishment of new standards for acceptable facility pressure and will provide the framework for extrapolating results from ground tests with finite facility pressure to space. The objectives are to 1) define sub-models ($\Theta_{e\perp}$; $\Theta_{e\parallel}$ from Table 2) for the dependence of ion and electron transport properties on local neutral density, 2) develop diagnostic and numerical capabilities to perform in-situ measurements of the local transport properties and neutral density, 3) combine the data streams from targeted kinetic model runs and experiments on HET plumes to calibrate and quantify uncertainty in the sub-models, 4) incorporate the sub-models into system-level HET and facility plume codes, 5) perform parametric system-level testing to refine model parameters, and 6) incorporate the refined system models in the PEM.

The presence of finite facility pressure is known to impact several key aspects of both HET and GIT operation. For example, for HETs, increasing facility pressure causes, the plume divergence to decrease (c.f. [65]),thrust to increase in a way that cannot be entirely explained by classical neutral ingestion (c.f. [66]), and the oscillation level to transition into new and unstable modes (c.f. [67]). In GITs, facility pressure can lead to anomalous plume mode operation that results in enhanced wear due to production of energetic ions [68], and electrical coupling processes can be suppressed. As a result of the latter effect, the neutralizer's true operating mode in space, and thus its true lifetime, may not be accurately indicated from ground tests. Taken together, these impacts on lifetime, stability, and performance cast doubt on the extensibility of ground tests to space.

The problem of finite facility pressure becomes even more pervasive for high-power thrusters. Modern facilities do not have sufficient pumping speed to accommodate the flow rates associated with 100-kW class thrusters. This is illustrated in Figure 7 where we see that for the 100-kW system, facilities cannot achieve the standards that have been used for qualification efforts for much lower power (~1 kW) thrusters [69]. While the pumping capabilities of facilities could, in principle, be improved using the standard technique of adding more active pumping area, there is only a finite amount of surface area in the chamber that can be covered. We anticipate that for high-power thruster testing, it may not be possible to create a test environment representative of space.

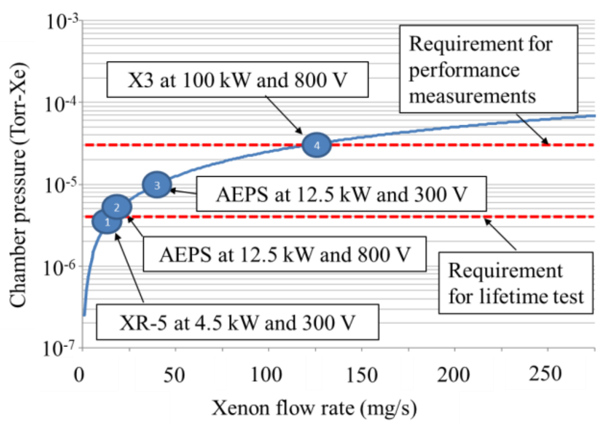

Figure 7 Chamber operating pressure versus xenon flow rate for the Large Vacuum Test Facility at the University of Michigan. The facility pumping speed is 550 kl/s on xenon. As a reference, requirements from the 1.35 kW class SPT-100 qualification program are also shown. Fig. adapted from Ref. [69].

G. Exemplar Project 2: Sputtering, Transport, and Deposition of Carbon

The goal of the project is to reduce uncertainty in models associated with the sputtering (Θ_s from Table 2), plume transport (H_P), and deposition of carbon (Θ_d), and use these models to generate system-level model ($H_{T:HET}, H_{T:GIT}; H_{T-P}$), predictions for thruster lifetime with quantified uncertainty. The objectives are to: (1) measure sputter yield of graphite under low-energy xenon bombardment and validate molecular dynamics (MD) simulations; (2) create a new CRDS laser or related optical diagnostic and use it to measure the density of carbon clusters sputtered from graphite surfaces as well as calibrate ionizer-equipped, electro-magneto-static probes; (3) develop and apply a new carbon isotope tracking diagnostic to measure carbon transport in ground-based facilities, and validate models of carbon transport through the relevant facility and thruster plume environments using PIC/DSMC; (4) mature experimental techniques for quantifying deposition, adsorption, and sticking coefficients of C and C clusters to thruster surfaces, and compare to models of these processes; and (5) employ diagnostics in system-level tests of high-power EP devices and measure the distribution of carbon and carbon cluster flux, transport, and deposition and compare with predictions from system-level models.

Accurately predicting the lifetime of high-power HET and GIT is critical for their use in future missions. Magnetically-shielded HETs have reduced erosion of channel walls [70]; however, magnetic shielding does give rise to carbon front pole cover erosion [71]. Previous research provides estimates for net erosion and deposition rates of thrusters with magnetic shielding [72, 73, 74, 75], and models predict carbon sputtered from the front pole covers is deposited on the center-mounted cathode, anode, and on the BN channel. A chief life-limiter for GITs is ion optics failure driven by charge exchange (CEX) erosion [76, 77]. At high power, the deposition of graphite onto grid surfaces affects the effective sputter yield of the grid, leading to erroneous lifetime predictions. The nature of the coatings is dependent on the ratio of the arrival rate of sputtered material to CEX-derived ion current to the grid. The morphology of the deposited films also affects the sputter yield. Hence, we judge that at high power, backsputtered facility carbon contamination will mask the true thruster erosion and deposition rates for both HET and GIT.

The possible presence of carbon clusters (C_2, C_3) complicates the facility contamination problem [78]. Previous models of facility carbon transport and deposition have neglected carbon clusters, instead of focusing on atomic carbon transport [79]. However, Oyarzabal *et al.* [80] observed C_2 and C_3 dimers and trimers as sputtered products in the incident xenon ion range of 50 to 225 eV, and their angular distributions are highly energy-dependent. We will develop a new CRDS technique to quantify the density of carbon C_2 clusters and correlate results with molecular dynamics simulations of atom and cluster sputtering from graphite surfaces. Carbon deposition on thruster surfaces modifies the electric potential distribution of the thruster, leading to carbon spalling and flaking, and electrical arcing (flares and sparks) between components. Further, contamination impacts electrical insulation, thermal radiation, and lifetime predictions. Recent results from accelerated 23,000-hr wear testing of a 6-kW HET show the effects of thick (>40 μm) layers of carbon on thruster surfaces [74]. Carbon deposition creates a thin film with conductivity increased by up to a factor of 1000 between high-voltage components. A thermal mismatch between deposited carbon and underlying substrate causes spalling. Carbon flakes can be up to 250 μm thick and 7-10 mm square. These flakes cause "sparks," "flares," and recycle events when they contact surfaces of different potentials and arc. We will investigate carbon layering, spalling, and flake formation with plasma-assisted carbon deposition experiments and corresponding high-fidelity simulations of thruster surface evolution due to carbon deposition.

H. Exemplar Project 3: Electrical Coupling

The goal of this project is to predict thruster stability associated with electrical coupling to the vacuum facility. This will include the development of tools and methodologies to define and understand the *standard electrical state*. This is the state where the power processing unit (PPU)-thruster-cathode-plume-facility coupling is sufficient to ensure all space-like electrical behavior is present in the ground test, or it can be extrapolated to in-space behavior. A definition of the standard electrical state and accompanying parameters will enable NASA to test high-power EP devices with confidence because a technique will guide the characterization of the circuit and the implementation of mitigation strategies. The objectives are to 1) define the necessary electrical parameters required to model the electrical circuit of the test facility, 2) configure an instrumented test facility for use in measuring temporal and spatial electrical coupling behavior, 3) create an instrumented, DC-DC power converter to investigate effects of PPU design on thruster coupling, and 4) develop parameterized electrical system models ($H_E; H_{E-pwr}; H_{T-pwr}$ from Table 2) and incorporate them into system-level thruster ($H_{T:GIT}; H_{T-P}$), cathode ($H_{T-P}; H_{T-c}; H_{c-P}$), and plume ($H_P; H_{T-P}; H_{P-E}$) models.

The ground-based testing environment must be representative of the in-space environment, or we must be able to correlate the test results to in-space behavior. Investigations show that PPU dynamics, cathode-plume coupling, and plasma beam neutralization through the conductive facility impact thruster performance and stability [81,83]. The challenges of electrical coupling are exacerbated by 100-kW EP in three ways. *First*, the increase in the thruster's physical size can impact the cathode's ability to couple to the thruster plume leading to discharge instabilities and displacement of the acceleration zone. *Second*, the physical size and density of the plume will create unexpected conduction paths that may mask inadequate neutralizer performance. *Third*, an increased number of CEX ions generated at elevated background pressure will lead to more conductive paths to the thruster body. Furthermore, many EP plasmas are dynamic systems, *e.g.*, the HET, resulting in plasma oscillatory modes that impact PPU coupling [8496] and may be worse at higher power. For GITs, poor electrical coupling of the neutralizer to the beam can yield an anomalous neutralizer plume mode that leads to increased neutralizer and grid wear [97].

Figure 8 shows an equivalent electrical circuit of a HET in a typical test facility [98]. The size and location of the acceleration region are known to be sensitive to pressure changes and thus impact many thruster parameters, including divergence angle, cathode coupling, thrust, and lifetime. It is unknown whether the location of the acceleration region is driven by or responding to the cathode coupling behavior.

Recent programs highlight the importance of predicting thruster stability when coupled with a PPU [99]. NASA requires the ability to predict electrical coupling and thruster stability because the facility pumping speeds and dimensions required to remove facility-induced CEX ions and achieve nearly complete neutralization through ion-electron recombination are prohibitive.

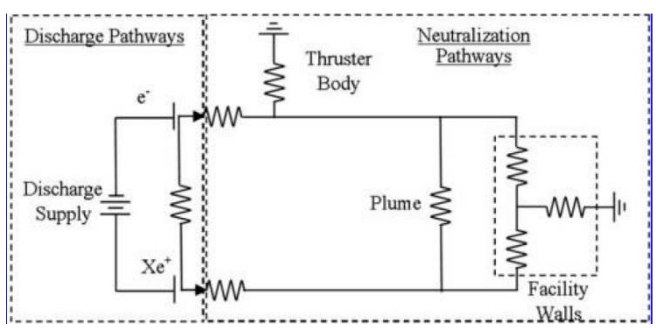

Figure 8 Notional diagram of the discharge circuit of HET and electron termination pathways in a ground-based test facility [98].

V. Products

JANUS will deliver several impactful research projects through the integrated efforts of the team members. These advances will be documented throughout the effort through conference and peer-reviewed publications and consolidated in the form of publicly available guidebooks.

1. **New insight to key fundamental processes related to facility effects**: The Institute's efforts—particularly through the dedicated fundamental and system-level studies—will lead to refined models and new physical insight into the facility-related processes that impact thruster behavior. Examples include refined models for sputtering at low energy, improved understanding of electron dynamics, and refined models for electrical coupling.
2. **Validated set of numerical tools for modeling facility effects at the system-level**: The PEMs, subsystem models (when possible), and underlying algorithm for predictions will be documented and made available to the general public. This will be accompanied by publications and guidebooks illustrating how to apply these tools.
3. **New diagnostic techniques**: Novel diagnostic techniques will be developed and documented, including new methods for neutral and carbon flux measurements.
4. **In-space predictions for several SOA thrusters**: The first three years of this effort will primarily focus on demonstrating the framework and approach to lower-power, SOA concepts, including several commercial thrusters. The data generated will be leveraged to provide key predictions that ultimately may be validated from in-space measurements.
5. **New standards for EP testing**: We will provide standards for a given thruster technology and power level for when a ground-test result, *e.g.*, performance, lifetime, or far-field plume, is representative of in-space performance ("test like you fly" conditions) or results can be extrapolated to space. An anticipated standard may include an upper bound on neutral flux as measured in the exit plane of the thruster. Best practices will also be provided for diagnostic implementation to yield the highest-fidelity measurements.
6. **Characterization of high-power EP**: JANUS will provide the first high-power measurements that may be extensible to space. Previous campaigns have encountered facility limitations.
7. **Upgraded facilities for high-power testing**: Both the GT and UM test facilities will be upgraded per the recommendations that emerge from this Institute to provide higher-fidelity test environments or high-power testing.
8. **Guidelines for facility upgrades and designs**: We will provide a detailed methodology for developing new facilities and modifying existing facilities to support high-power EP tests. The recommendations will be informed by the PEM framework.
9. **Guidelines and methodologies for extrapolating from facilities to space**: Methodologies will be based on combining the PEM framework with experimental measurements from the facility. Recommendations will include what modules to include in the PEM predictions for a given facility, how to employ OED to determine the most impactful facility configurations and measurements for reducing uncertainty in the PEM extrapolation, and methods for performing the extrapolation. Recommendations will include best practices for running the thruster, *e.g.*, the electrical configuration for the thruster body, to make the test more representative of space.

External Interactions

An external, independent Institute Advisory Board (IAB) composed of experts from the Air Force, Aerojet Rocketdyne, Busek, Lockheed Martin, and Orbion, provides a top-level assessment of research progress and resource utilization to balance the strong academic perspective of JANUS. IAB members come from industry, government, non-profit organizations, and academia. The members span the full spectrum of relevant expertise, including EP, materials science systems integration, and spacecraft architecture. The IAB formally engages JANUS with reviews of the six-month reports and at the annual reviews to evaluate the progress and plans of JANUS. To address the conflicts of interest of the leadership team, the independent, external evaluations and recommendations of the IAB carry significant influence in decision-making and assessment.

JANUS will engage multiple external organizations relevant to the EP community to promote knowledge and information sharing and student opportunities and experiences. Specific external organizations include NASA MSFC, NASA GRC, JPL, the AFRL, NRL, and EP start-up companies and spacecraft integrators, including Northrup Grumman, and Maxar/SSL. We include these organizations in our monthly seminars to promote interaction, collaboration, and information exchange that is especially beneficial for students.

VI. Conclusion

The effort will deliver several new tools, strategies, and guidelines for evaluating existing infrastructure and designing new infrastructure for testing high-power EP. These include validated models for the response of HETs and GITs to the facility, new physics-based standards for testing and modeling that encapsulate best practices for mitigating and/or compensating for facility effects, and new standardized diagnostic techniques for characterizing the effects of the facility on thruster operation. We will collaborate with government and industry partners to incorporate our advancements into present and future research and development processes. Furthermore, JANUS will employ and graduate many university graduate students. Our work will transform them into engineers and scientists with the skills needed to enable the development of high-power EP technology. *Just as the Roman god Janus stood at the intersection of new beginnings, so will this Institute represent a crucial gateway for the transition of the next generation of propulsion technologies for space exploration from the laboratory to space*.

Acknowledgments

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