

Eagleworks Laboratories: Advanced Propulsion Physics Research

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ABSTRACT

NASA/JSC is implementing an advanced propulsion physics laboratory, informally known as "Eagleworks", to pursue propulsion technologies necessary to enable human exploration of the solar system over the next 50 years, and enabling interstellar spaceflight by the end of the century. This work directly supports the "Breakthrough Propulsion" objectives detailed in the NASA OCT TA02 In-space Propulsion Roadmap, and aligns with the #10 Top Technical Challenge identified in the report. Since the work being pursued by this laboratory is applied scientific research in the areas of the quantum vacuum, gravitation, nature of space-time, and other fundamental physical phenomenon, high fidelity testing facilities are needed. The lab will first implement a low-thrust torsion pendulum (<1 uN), and commission the facility with an existing Quantum Vacuum Plasma Thruster. To date, the QVPT line of research has produced data suggesting very high specific impulse coupled with high specific force. If the physics and engineering models can be explored and understood in the lab to allow scaling to power levels pertinent for human spaceflight, 400kW SEP human missions to Mars may become a possibility, and at power levels of 2MW, 1-year transit to Neptune may also be possible. Additionally, the lab is implementing a warp field interferometer that will be able to measure spacetime disturbances down to 150nm. Recent work published by White [1] [2] [3] suggests that it may be possible to engineer spacetime creating conditions similar to what drives the expansion of the cosmos. Although the expected magnitude of the effect would be tiny, it may be a "Chicago pile" moment for this area of physics.

INTRODUCTION

NASA/JSC is implementing an advanced propulsion physics laboratory, informally known as Eagleworks", to pursue propulsion technologies necessary to enable human exploration of the solar system over the next 50 years, and enabling interstellar spaceflight by the end of the century. This work directly supports the "Breakthrough Propulsion" objectives detailed in the NASA OCT TA02 In-space Propulsion Roadmap(2.3.7), and aligns with the #10 Top Technical Challenge identified in the report: Pursue investigation and development of advanced in-space propulsion technologies (TRL < 3). Since the work being pursued by this laboratory is applied scientific research in the areas of the quantum vacuum, gravitation, nature of space-time, and other fundamental physical phenomenon, high fidelity testing facilities are needed. The lab will first implement a low-thrust torsion pendulum (<1 uN), and commission the facility with an existing Quantum Vacuum Plasma Thruster. The lab will eventually incorporate an interferometer to be used to measure York Time effects of test devices (expansion/contraction of space)

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RESULTS AND DISCUSSION

TORSION PENDULUM

Construction of the torsion pendulum is progressing. The framework for the torsion pendulum is complete, and the custom low-torsion linear flexure bearings manufactured by Riverhawk have been installed in the rig. A custom electrostatic paddle system [4] is used to provide a non-contact calibration force, and calibration of the system has been completed. The paddle system consists of two aluminum cylinders, with a minor diameter of 0.5 inches. The theoretical equation for the force is:

$$F = \frac{1}{2} \epsilon_0 \left(\frac{V}{L} \right)^2 A$$

F is the force, V is the charge voltage, L is the separation gap, and A is the area of the cylindrical paddle. The empirical data results versus theoretical is shown in Figure 1. The calibration of the paddles indicates an approximate 5% as-manufactured deviation from the theoretical equation. The calibration of the paddles was done using a Fluke 343A DC Voltage Calibrator (0-1000V), and the force was measured using a Scientech SA210 scientific balance. For each calibration run, the positively charged paddle is placed on the balance, isolated by an acrylic mounting block, and the grounded paddle is accurately positioned over the positive paddle using optic bench micro-positioning stages capable of all the necessary degrees of freedom.

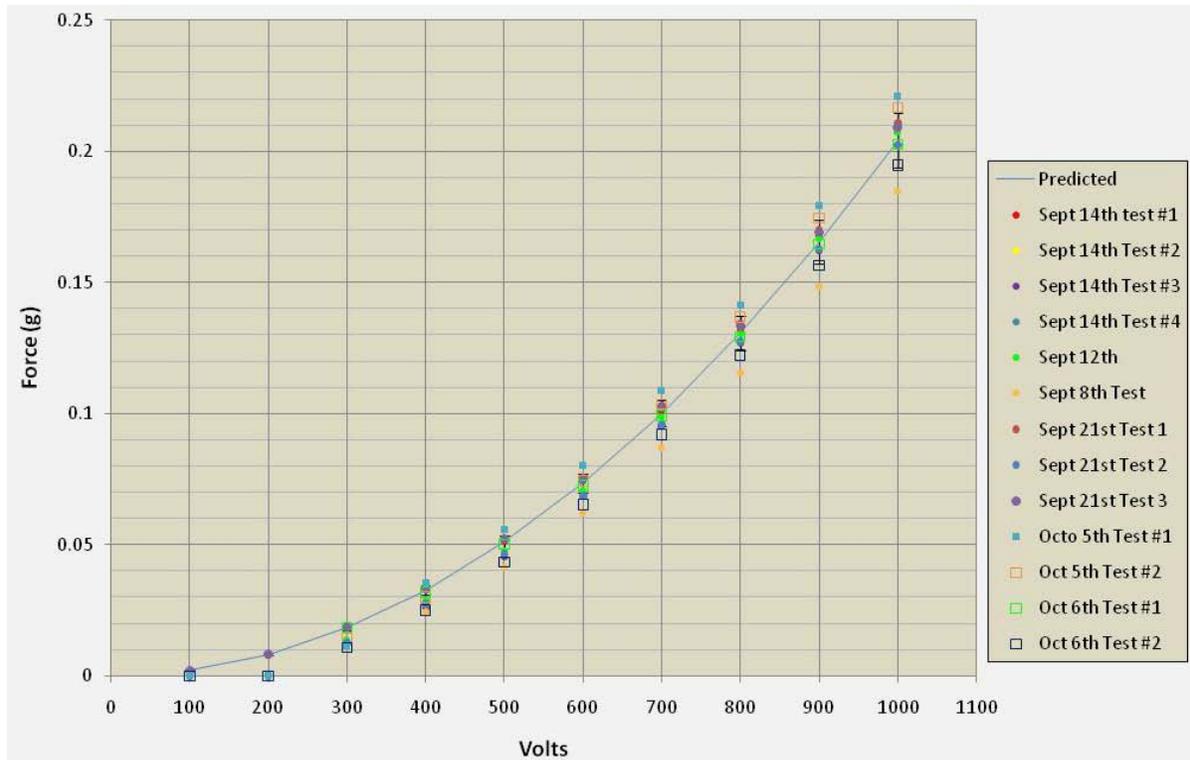


Figure 1 Calibration Data for Electrostatic Paddle System

The paddle system has been mounted to the torsion pendulum by adapting a NRC FP-2 Fiber Optic Positioner (5-axis). The grounded paddle is mounted to the torsion balance arm, and continuity is accomplished by passing the ground through the linear flexure bearings, eliminating an extra wire that can be a source of spurious torque across the interface. Force produced by a test article will be

accomplished by using an accurate optical displacement sensor system, the Philtec muDMS-D63Bv1C1ET1, and converting the measured displacement of the far end of the torsion balance arm to a force by using the calibration system just discussed. Figure 2 shows both systems being roughed in on the torsion pendulum prior to being installed in the vacuum chamber. The relative placement of the optical displacement sensor relative to the paddle system will be accomplished by using the axial stage on the positive paddle to initiate contact between the positive and negative paddles (power supply off!), and use the optical displacement sensor to establish the moment of contact deduced by steady increase in distance. This will provide as-installed relative positioning of the optical displacement sensor and paddle, so the optical displacement sensor can be used to determine the paddle separation when a calibration pulse is initiated prior to testing a test article. Passive magnetic dampers will be added to the torsion balance arm as well. Two approaches are being considered to pass power and data across the interface to a test article. JPL has provided guidance on inputs on wire selection and mounting to establish an effective interface without sacrificing fidelity (< 1 micro Newton). Some additional discussion is taking place about using a liquid metal interface approach to eliminate all systematic torque. The torsion pendulum will be used to evaluate performance of several quantum vacuum plasma thruster test articles.

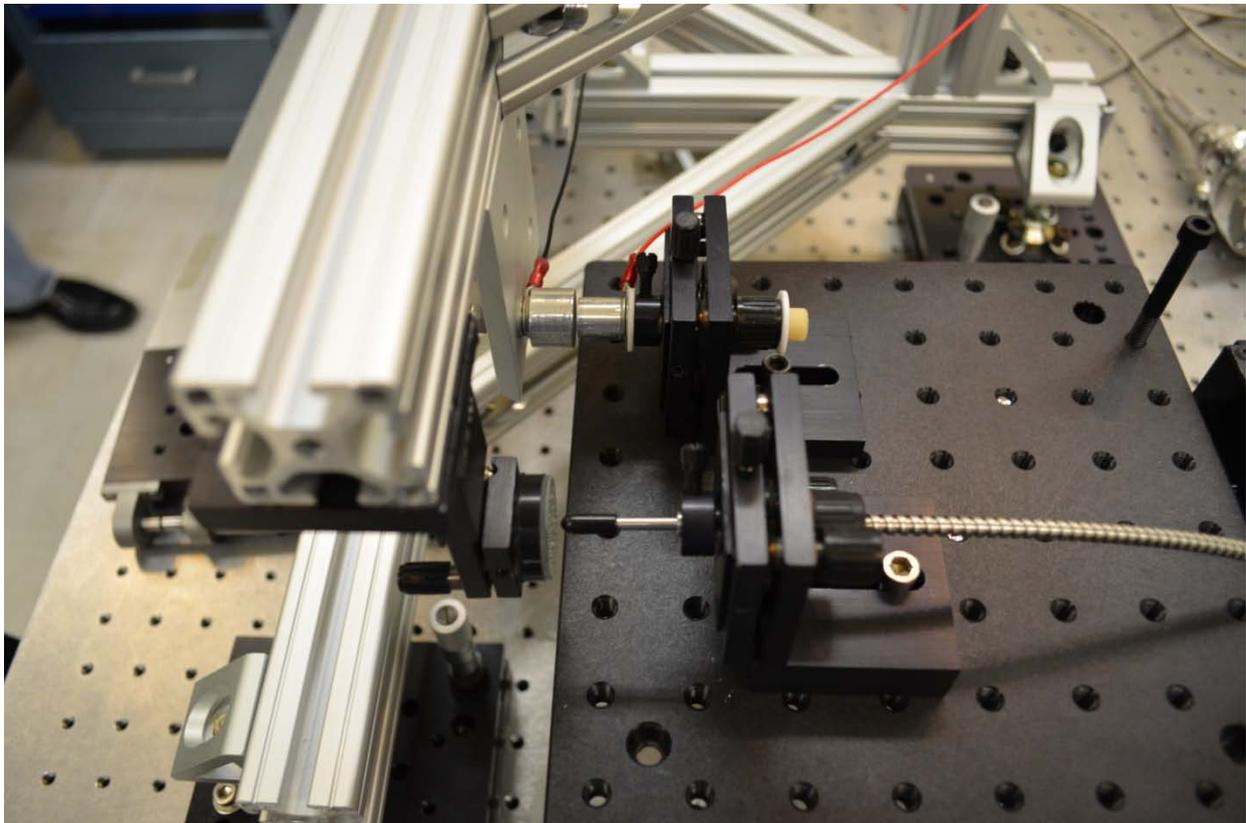


Figure 2: Electrostatic Paddle Force Calibration System and Philtec Optical Displacement Sensor mounting

QUANTUM VACUUM PLASMA THRUSTERS (Q-THRUSTERS)

Can the properties of the quantum vacuum be used to propel a spacecraft? The idea of pushing off the vacuum is not new, in fact the idea of a “quantum ramjet drive” was proposed by Arthur C. Clark

(proposer of geosynchronous communications satellites in 1945) in the book *Songs of Distant Earth* in 1985: "If vacuum fluctuations can be harnessed for propulsion by anyone besides science-fiction writers, the purely engineering problems of interstellar flight would be solved." [5]. When this question is viewed strictly classically, the answer is clearly no, as there is no reaction mass to be used to conserve momentum. However, QED, which has made predictions verified to 1 part in 10 billion, also predicts that the quantum vacuum (lowest state of the electrodynamic field) is not empty, but rather a sea of virtual particles and photons that pop into and out of existence stemming from the Heisenberg uncertainty principle. The Dirac vacuum, an early vacuum model, predicted the existence of the electron's antiparticle, the positron in 1928, which was later confirmed in the lab by Carl Anderson in 1932. Confirmation that the QV would directly impact lab observations came inadvertently in 1948 while Willis Lamb was measuring the 2s and 2p energy levels in the hydrogen atom. Willis discovered that the energy levels were slightly different, contrary to prediction, but detailed analysis performed within weeks of the discovery by Bethe at Cornell predicted the observed difference only when factoring in contributions from the QV field. The Casimir force, derived in 1948 by Casimir in response to disagreements between experiment and model for precipitation of phosphors used with fluorescent light bulbs, predicts that there will be a force between two nearby surfaces due to fluctuations of the QV. This force has been measured and found to agree with predictions numerous times in multiple laboratories since its derivation.

What is the Casimir force? The Casimir force is a QV phenomenon such that two flat plates placed in close proximity in the vacuum preclude the appearance of particles, whose wavelength is larger than the separation gap, and the resultant negative pressure between the two surfaces is more negative than the pressure outside the two surfaces, hence they experience an attractive force. A historical, classical analog to the idea behind the Casimir Force can be drawn considering training given to sailors of the tall-ship era who were instructed to not allow two ships to get too close to one another in choppy seas lest they be forced together by the surrounding waves requiring assistance to be pulled apart. Although the forces have typically been small, from a practical perspective, micro-electromechanical systems (MEMS) are already utilizing this phenomenon in design application.

How much energy is in the Quantum Vacuum? The theoretical calculation for the absolute zero ground state of the ZPF can be calculated using the following equation[6]:

$$E_0 = \int_{\omega=0}^{\omega_{cutoff}} \frac{\hbar \omega^3}{2\pi^2 c^3} d\omega$$

Using the Plank frequency as upper cutoff yields a prediction of $\sim 10^{114}$ J/m³. Current astronomical observations put the critical density at $1 \cdot 10^{-26}$ kg/m³. The vast difference between QED prediction and observation is not currently understood.

Is there a way to utilize this sea of virtual particles and photons (radiation pressure) to transfer momentum from a spacecraft to the vacuum? A number of approaches have been detailed in the literature: Vacuum sails that develop a net force by having materials on either side with different optical properties; Inertia control by altering vacuum energy density and reducing total spacecraft mass thus minimizing kinetic energy and amount of work needed to accelerate a spacecraft; and dynamic systems that make use of the dynamic Casimir force to generate a net force.

What is the dynamic Casimir force? The dynamic Casimir force arises as a result of Unruh radiation where an accelerated observer sees the vacuum as a higher temperature photon bath, and is the mechanism that facilitates Hawking radiation around a black hole where relativistic acceleration

separates a virtual pair such that one particle goes in the horizon, while the other escapes. Recent findings reported earlier in 2011 show that the dynamic Casimir effect may have been detected in the lab [7]. The simplest mechanical construct to help visualize using the dynamic Casimir force to generate thrust is through the use of vibrating mirrors where the mirror trajectory is designed to generate radiation in a preferred direction. The magnitude of thrust arising from using the dynamic Casimir force derived numerous times in the literature has been shown to be very small in comparison with conventional propulsion systems, but has been clearly shown to be theoretically possible. As a classical construct to help with visualization, consider how a submarine uses a propeller to create a hydrodynamic pressure gradient that propels the sub forward while the receding water column carries the momentum information downstream. The sub does not carry a tank of water and then flow that water across the propeller; rather it uses the propeller to interact with the environment. The corollary is that there has to be a “wake” (conservation of momentum is required!).

Are there methods to increase net force? As the calculated energy density of the quantum vacuum versus observation shows, even though QED is one of the most experimentally successful theories to date, the community’s understanding of the vacuum is only just beginning as this is a new field, and the study of the quantum vacuum is at the leading edge of science with a wide open horizon to explore. Recent models developed by White suggests that there are ways to increase the net force, and these models have been validated against data at both the cosmological scale, the quantum level, and test devices have been fabricated/tested in the lab and found to agree with model predictions. Figure 3 depicts the principles of q-thruster operation in tabular form.

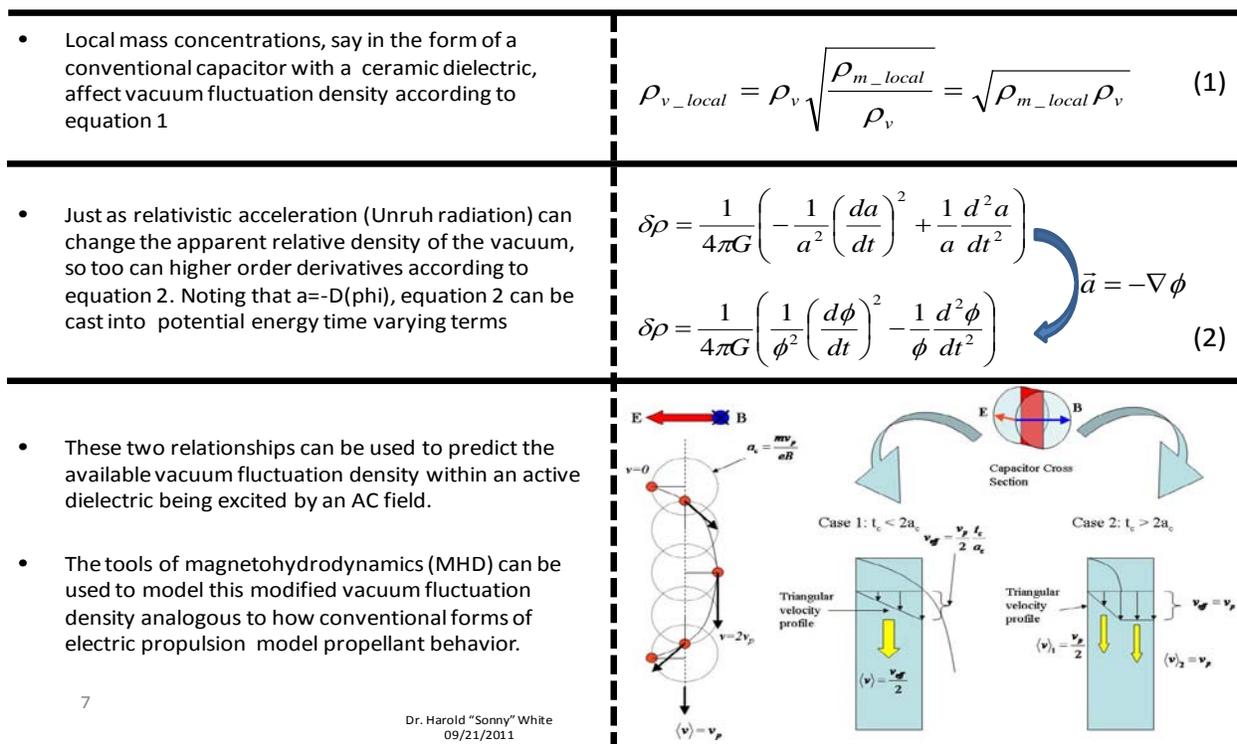


Figure 3: Principles of Q-thruster Operation

How does a Q-thruster work? A Q-thruster uses the same principles and equations of motion that a conventional plasma thruster would use, namely Magnetohydrodynamics (MHD), to predict propellant behavior. The virtual plasma is exposed to a crossed E and B-field which induces a plasma drift of the entire plasma in the $E \times B$ direction which is orthogonal to the applied fields. The difference arises in the fact that a Q-thruster uses quantum vacuum fluctuations as the fuel source eliminating the need to carry propellant. This suggests much higher specific impulses are available for QVPT systems limited only by their power supply's energy storage densities. Historical test results have yielded thrust levels of between 1000-4000 micro-Newtons, specific force performance of 0.1N/kW, and an equivalent specific impulse of $\sim 1 \times 10^{12}$ seconds. Figure 4 shows a test article and the thrust trace from a 500g load cell [8].

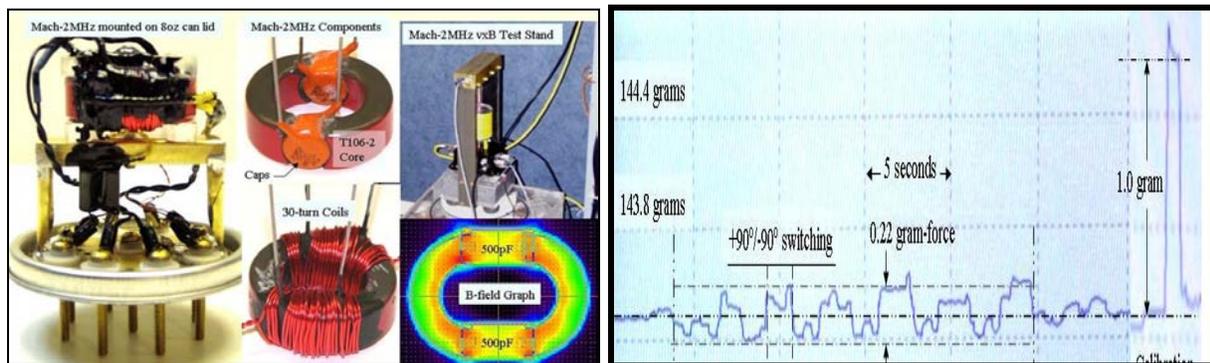


Figure 4: 2005 test article construction and results

The near term focus of the laboratory work is focused on gathering performance data to support development of a Q-thruster engineering prototype targeting Reaction Control System (RCS) applications with force range of 0.1-1 N with corresponding input power range of 0.3-3 kW. Up first will be testing of a refurbished test article to duplicate historical performance on the high fidelity torsion pendulum (1-4 mN at 10-40 W). The team is maintaining a dialogue with the ISS national labs office for an on orbit DTO.

How would Q-thrusters revolutionize human exploration of the outer planets? Making minimal extrapolation of performance, assessments show that delivery of a 50 mT payload to Jovian orbit can be accomplished in 35 days with a 2 MW power source [specific force of thruster (N/kW) is based on potential measured thrust performance in lab, propulsion mass (Q-thrusters) would be additional 20 mT (10 kg/kW), and associate power system would be 20 mT (10 kg/kW)]. Q-thruster performance allows the use of nuclear reactor technology that would not require MHD conversion or other more complicated schemes to accomplish single digit specific mass performance usually required for standard electric propulsion systems to the outer solar system. In 70 days, the same system could reach the orbit of Saturn. Figure 5 illustrates the performance capabilities of this advanced propulsion concept for transforming outer solar system exploration (delta-v's come from [9]).

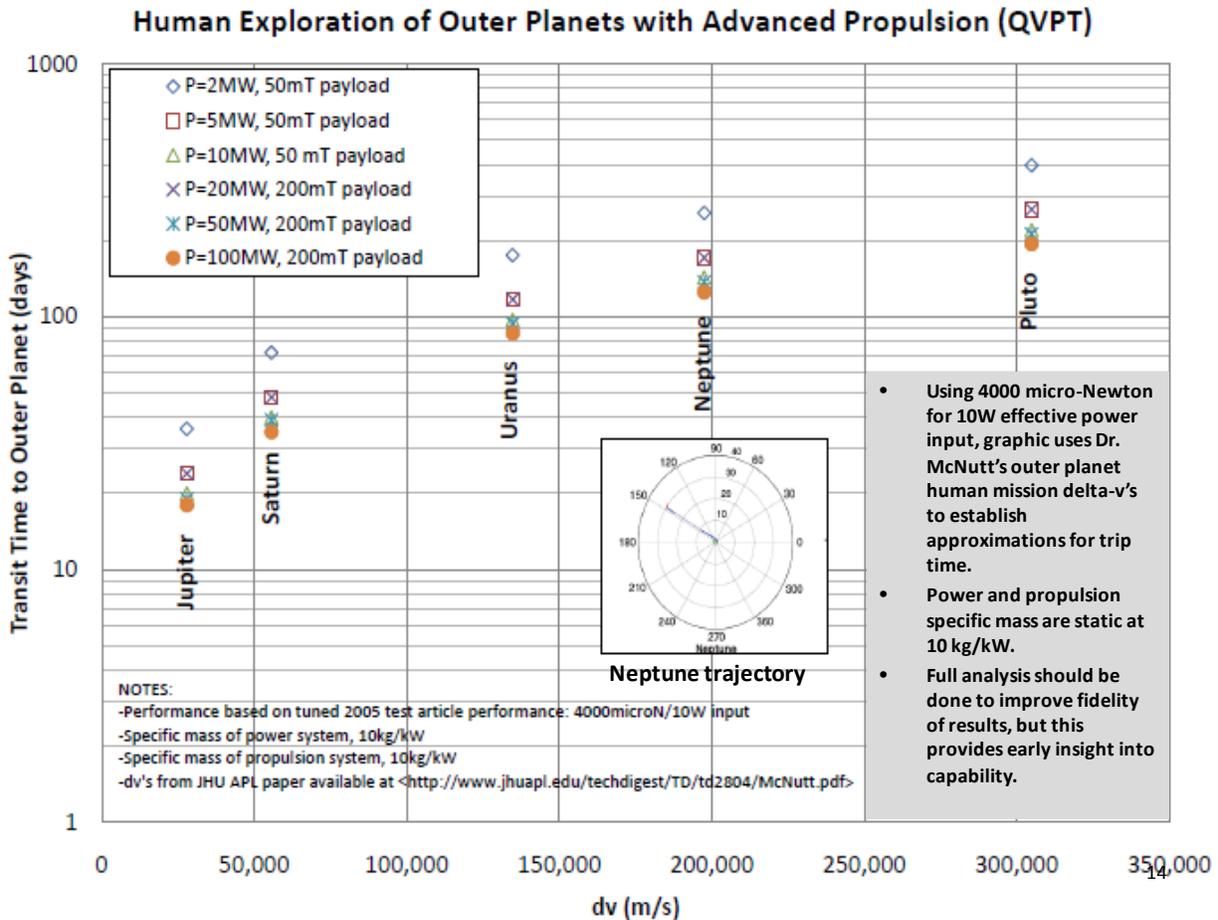


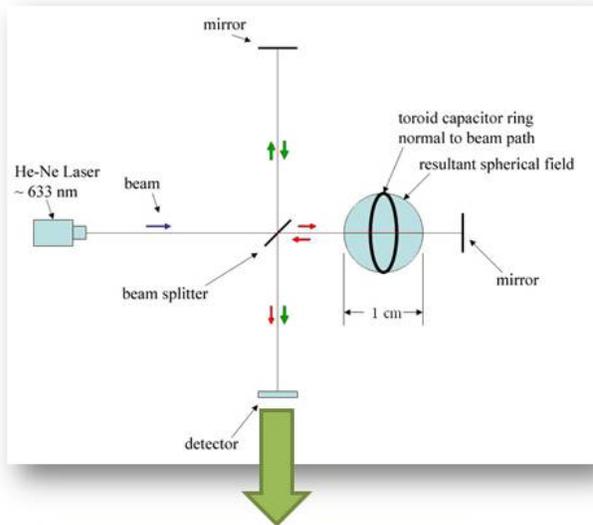
Figure 5: Q-thruster performance for outer solar system exploration

WARP FIELD INTERFEROMETER

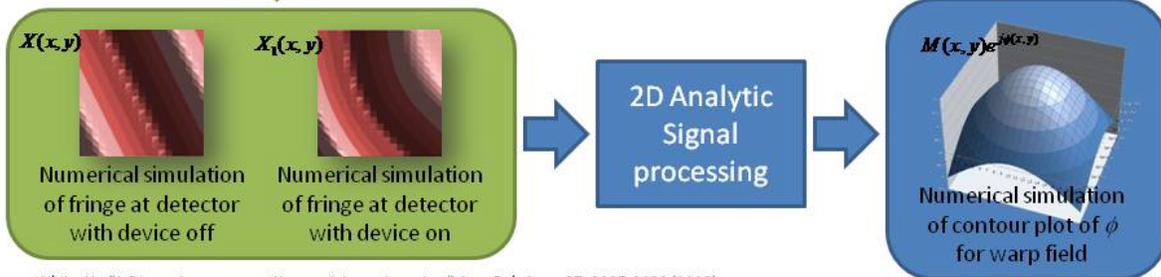
Recent work published by White [1][2][3] suggests that it may be possible to engineer spacetime creating conditions similar to what drives the expansion of the cosmos. The canonical form of the Alcubierre metric as derived in [2] provides new insight into how a test device could be constructed to generate say a spherical region of perturbation of ~1 cm diameter. Figure 5 depicts the graphical layout of a warp field interferometer experiment capable of measuring possible York Time perturbations within a small (~1cm) spherical region. Across 1cm, the experimental rig should be able to measure space perturbations down to ~1 part in 10,000,000. As previously discussed, the canonical form of the metric suggests that boost may be the driving phenomenon in the process of physically establishing the phenomenon in a lab. Further, the energy density character over a number of shell thicknesses suggests that a toroidal donut of boost can establish the spherical region. Based on the expected sensitivity of the rig, a 1cm diameter toroidal test article (something as simple as a very high-voltage capacitor ring) with a boost on the order of 1.0000001 is necessary to generate an effect that can be effectively detected by the apparatus. The intensity and spatial distribution of the phenomenon can be quantified using 2D analytic signal techniques comparing the detected interferometer fringe plot with the test device off with the detected plot with the device energized. Figure 5 also has a numerical example of what the before and after fringe plots may look like with the presence of a spherical disturbance of the strength just discussed.

While this would be a very modest instantiation of the phenomenon, it would likely be Chicago pile moment for this area of research.

White-Juday Warp Field Interferometer



- White-Juday Warp Field Interferometer uses He-Ne laser to generate interference signal at a detector with test device placed in proximity to one leg of beam path to evaluate York-Time effects (expansion/contraction of space).
- He-Ne laser beam ($\lambda = 633 \text{ nm}$) is split allowing one part of beam to pass near /through device being tested.
- Presence of warp field region will induce relative phase shift between split beams that should be detectable provided magnitude of phase shift is sufficient.
- Using 2D Analytic Signal processing of the , the Magnitude and phase of the field can be extracted for study and comparison to theoretical models.



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Figure 5: Warp Field Interferometer layout (here, ϕ is the phase angle).

SUMMARY AND CONCLUSIONS

This paper has chronicled the latest developments in the process of establishing an advanced propulsion physics lab and identified two main lines of research. The one line associated with quantum vacuum plasma thrusters is a near term effort that is in the middle of shifting out of a pure physics focus and on to engineering, while the other is very much a fundamental physics pursuit. The benefits of the near term effort was discussed and some objectives for the next few test articles were discussed to help establish a roadmap of sorts to develop a test article for on-orbit use, and near term systems applications (RCS first, then possibly main propulsion). As the OCT TA02 roadmap indicated, one of the important challenges for the Agency in the pursuit of developing bold exploration missions is to ensure that there is a sustained level of modest funding for the "seed corn" advanced propulsion and power technologies that must be explored to identify greatly enabling technologies. The Advanced Propulsion Physics Laboratory, Eagleworks at JSC is a step back into this tradition of the Agency and should be pursued by other centers and other Agencies. Godspeed!

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