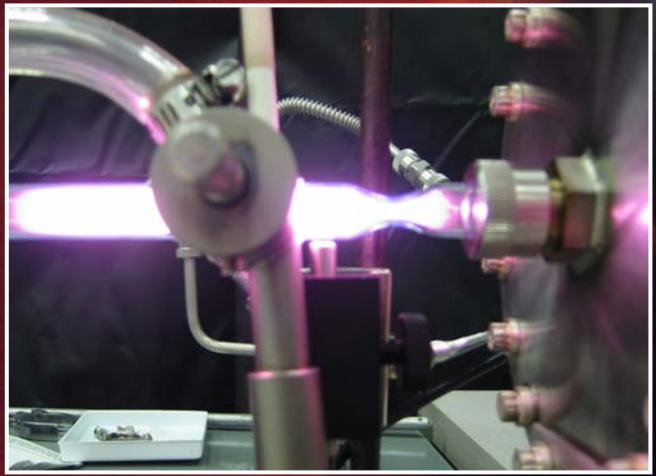
NASA INSTITUTE FOR ADVANCED CONCEPTS PHASE I FINAL PRESENTATION
ATLANTA, GA, OCTOBER 25, 2002

THE BLACKLIGHT ROCKET ENGINE

A PHASE I STUDY FUNDED BY THE NASA INSTITUTE FOR ADVANCED CONCEPTS



ANTHONY J. MARCHESE
PETER M. JANSSON
JOHN L. SCHMALZEL

COLLEGE OF ENGINEERING
ROWAN UNIVERSITY
GLASSBORO, NJ 08028

http://engineering.rowan.edu/~marchese

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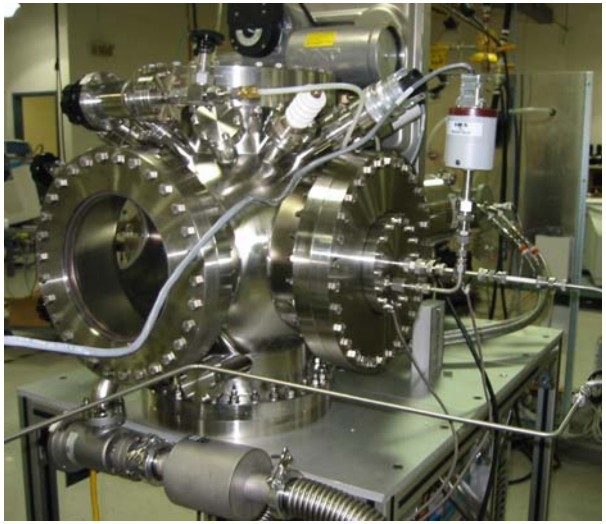
THE BLACKLIGHT ROCKET ENGINE

OVERVIEW OF PRESENTATION

- Background on H_2 mixed gas plasmas
- Objectives of the Phase I study
- Evaluation of previous data and new experiments on H_2 mixed gas plasmas
- Thruster hardware design and development
- Experimental approach for thruster performance testing
- Test firing of BLPT and BLMPT thrusters
- Ongoing and future work



BLPT Thruster in Test Configuration

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Background

Experimental Data on High Energy Mixed Gas H_2 Plasma Systems

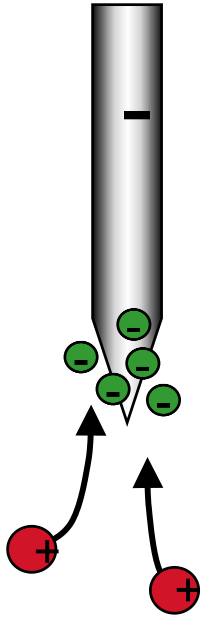
For the past decade, researchers have reported unique spectroscopic results for mixed gas hydrogen plasmas generated in:

- **Glow discharge systems** (Kuraica and Konjevic, 1992; Videnovic, *et al.,* 1996)
- **RF discharge systems** (Djurovic and Roberts, 1993; Radovanov, *et al.,* 1995)
- **Microwave systems** (Hollander and Wertheimer, 1994)

In these experiments, researchers have measured:

- **Excessive Doppler line broadening of H emission lines**
- **Peculiar non-Boltzmann population of excited states.**

The hydrogen line broadening in these studies was attributed to acceleration of hydrogen ions in the vicinity of the cathode and subsequent emission as it picks up an electron near the cathode.

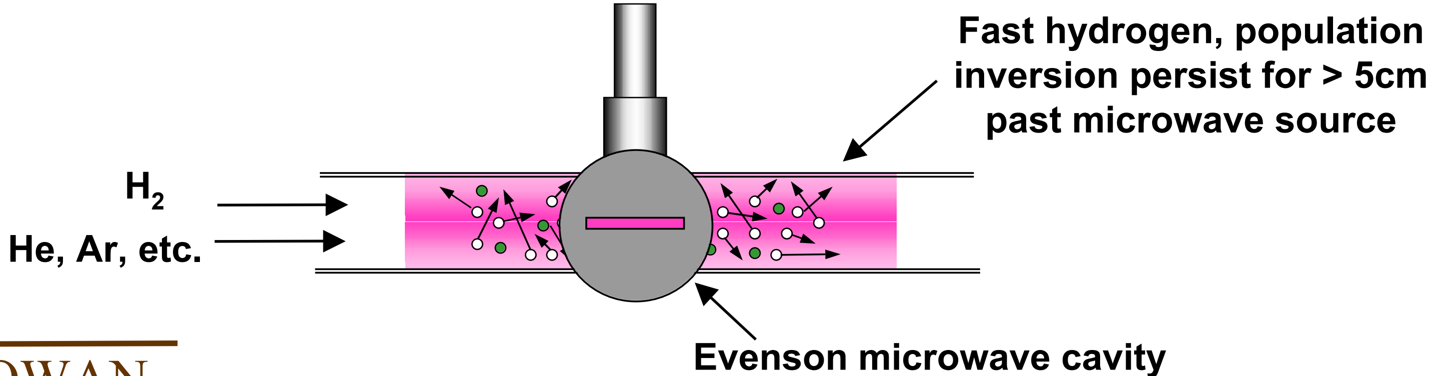


BACKGROUND

THE BLACKLIGHT PROCESS

More recently, the following data have been published by BlackLight Power reporting similar phenomena under different conditions:

- **Preferential Doppler line broadening of atomic hydrogen emission spectra** (Mills and Ray, 2002).
- **Inverted populations of hydrogen Balmer series in microwave hydrogen gas mixture plasmas** (Mills, Ray and Mayo, 2002).
- **Novel vacuum ultraviolet (VUV) vibration spectra of hydrogen mixture plasmas** (Mills, He, Echezuria, Dhandapani and Ray, 2002).
- **Water bath calorimetry experiments showing increased heat generation in certain gas mixtures** (Mills, Ray, Dhandapani, Nansteel, Mayo, *et al*., 2002).



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THE BLACKLIGHT ROCKET ENGINE

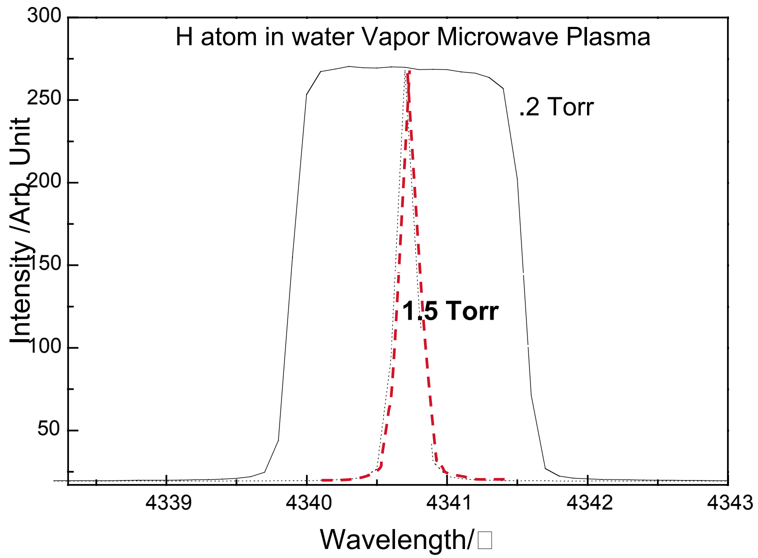
OBJECTIVES OF THE PHASE I STUDY

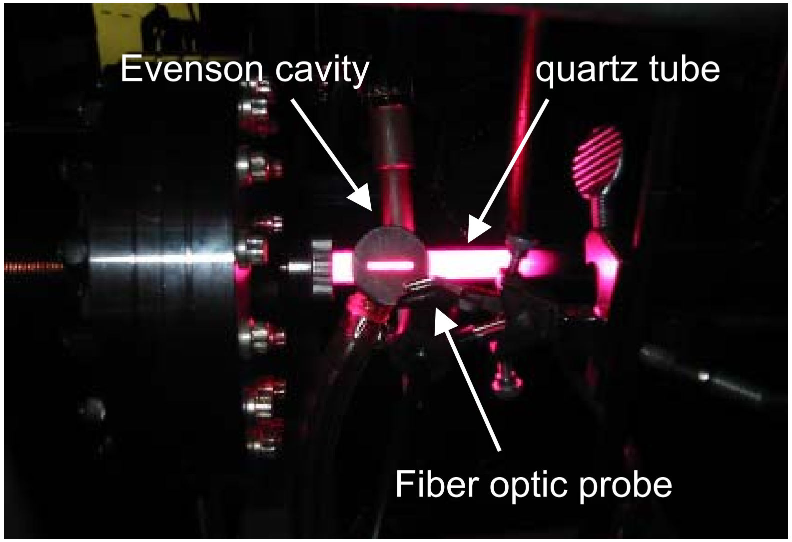
The objectives of the Phase I study were as follows:

- **Perform experiments to evaluate previously published data on energetic mixed gas H_2 plasmas.**
- **Develop bench scale proof-of-concept BlackLight Plasma Thruster (BLPT) and BlackLight Microwave Plasma Thruster (BLMPT) hardware.**
- **Develop experimental apparatus for measuring specific impulse (I_{sp}) and overall thruster efficiency (η).**
- **Measure specific impulse (I_{sp}) and overall thruster efficiency (η) when operating the BLPT and/or BLMPT thrusters.**

EVALUATION OF EXPERIMENTAL DATA

DOPPLER LINE BROADENING OF H EMISSION SPECTRA IN H_2O MICROWAVE PLASMAS





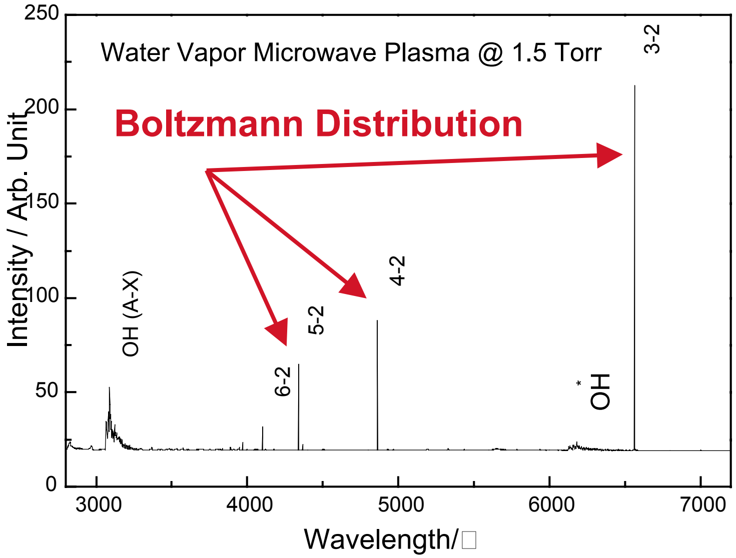
An Evenson microwave discharge cavity (Fehsenfeld, *et al.* 1964) **was used to excite water vapor plasmas at various pressures.**

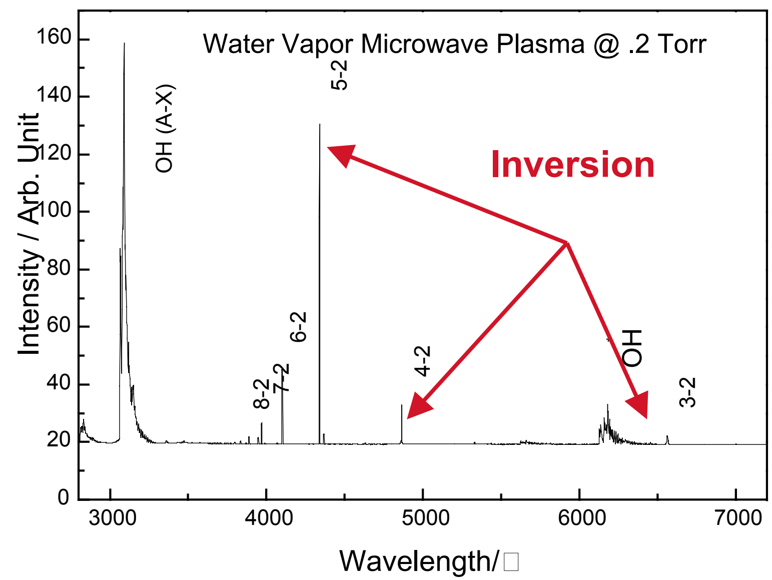
Preferential Doppler line broadening was observed in atomic hydrogen emission spectra. Results suggest extremely high random translational velocity of H atoms within the plasma.

No broadening was observed in oxygen spectra.

EVALUATION OF EXPERIMENTAL DATA

INVERSION OF LINE INTENSITIES IN HYDROGEN BALMER SERIES





Using the same apparatus used for the line broadening experiments, an inversion of line intensities of the hydrogen Balmer series were observed in H_2O plasmas.

These results suggest the presence of a previously unobserved pumping mechanism.

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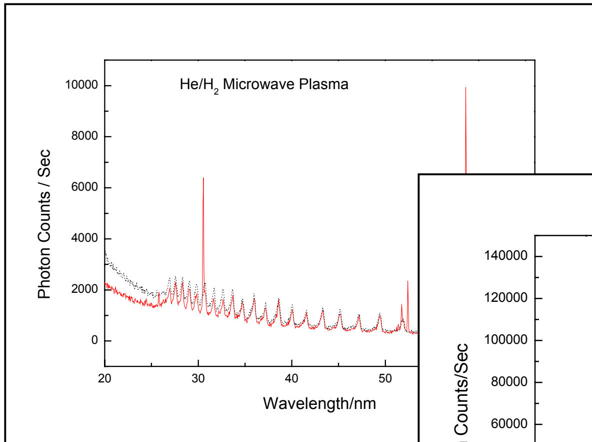
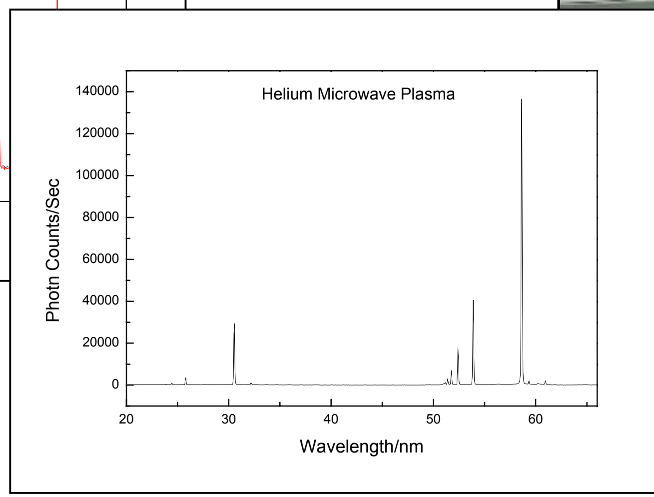
EVALUATION OF EXPERIMENTAL DATA

NOVEL VACUUM ULTRAVIOLET (VUV) VIBRATION SPECTRA IN H_2 GAS MIXTURES





A McPherson Model 248/310G 4° grazing incidence VUV spectrometer was used to measure vacuum ultraviolet emission (25 to 90 nm) for helium and hydrogen/helium microwave plasmas.

The He/H_2 microwave plasmas show novel “vibrational’ peaks in the VUV.

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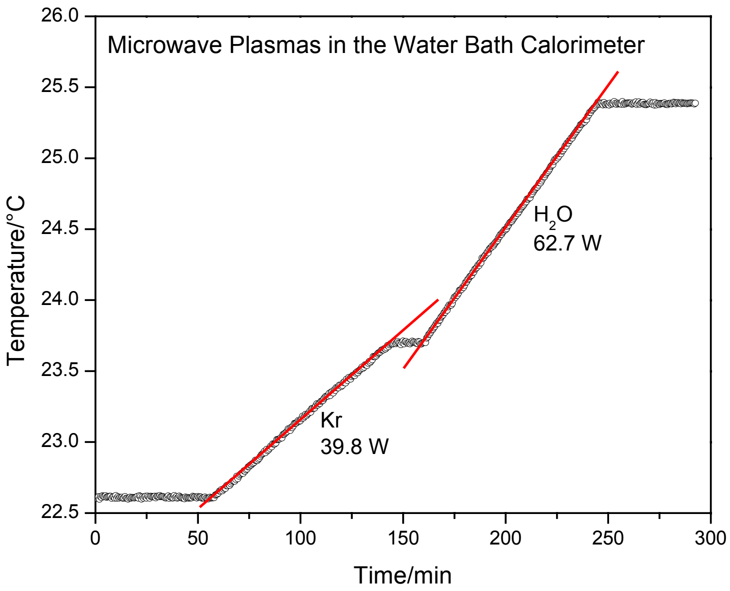
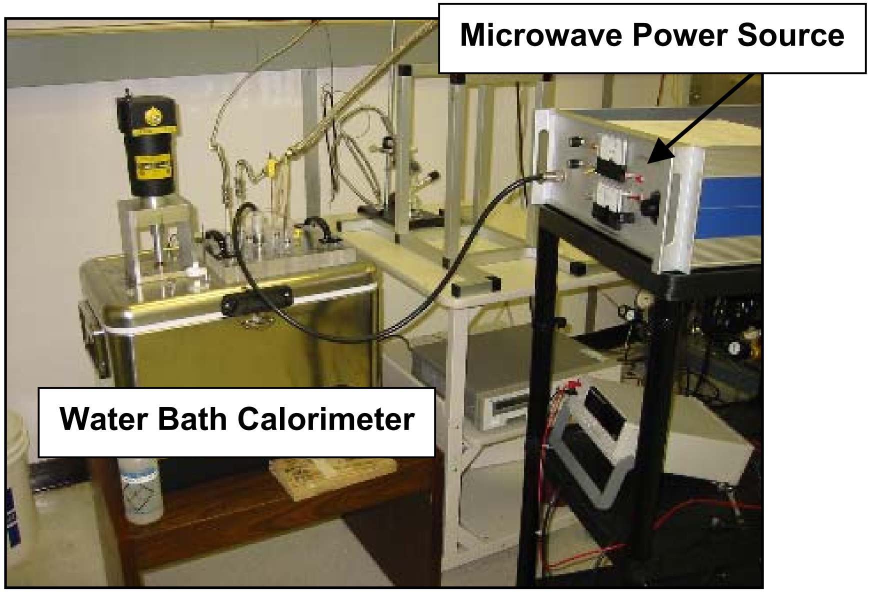
Evaluation of Experimental Data

Water Bath Calorimetry Experiments Showing Increased Heat Generation





An Evenson cavity and quartz plasma tube were installed into a stainless steel housing and immersed in a water bath calorimeter (accuracy of +/- 1 W).

For a forward microwave power of 70 W and reflected power of 16 W, control gas plasmas consistently transfer < 40 W into the water while H_2/catalyst mixtures transfer 55 to 62 W.

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THE BLACKLIGHT PROCESS

THEORETICAL EXPLANATION OF DATA SUGGESTED BY MILLS, *et al.* (2000).

Bohr (1913) and later Schrödinger (1927) developed theories that predict the observed energy levels of the electron in a hydrogen atom according to the following equation:

$$E_n = -\frac{e^2}{n^2 8\pi\varepsilon_o a_o} = -\frac{13.598\text{eV}}{n^2}$$

$$n = 1,2,3,4,\ldots$$

where a_o is the ground state radius of the hydrogen atom, ε_o the permittivity constant and n the principal quantum number.

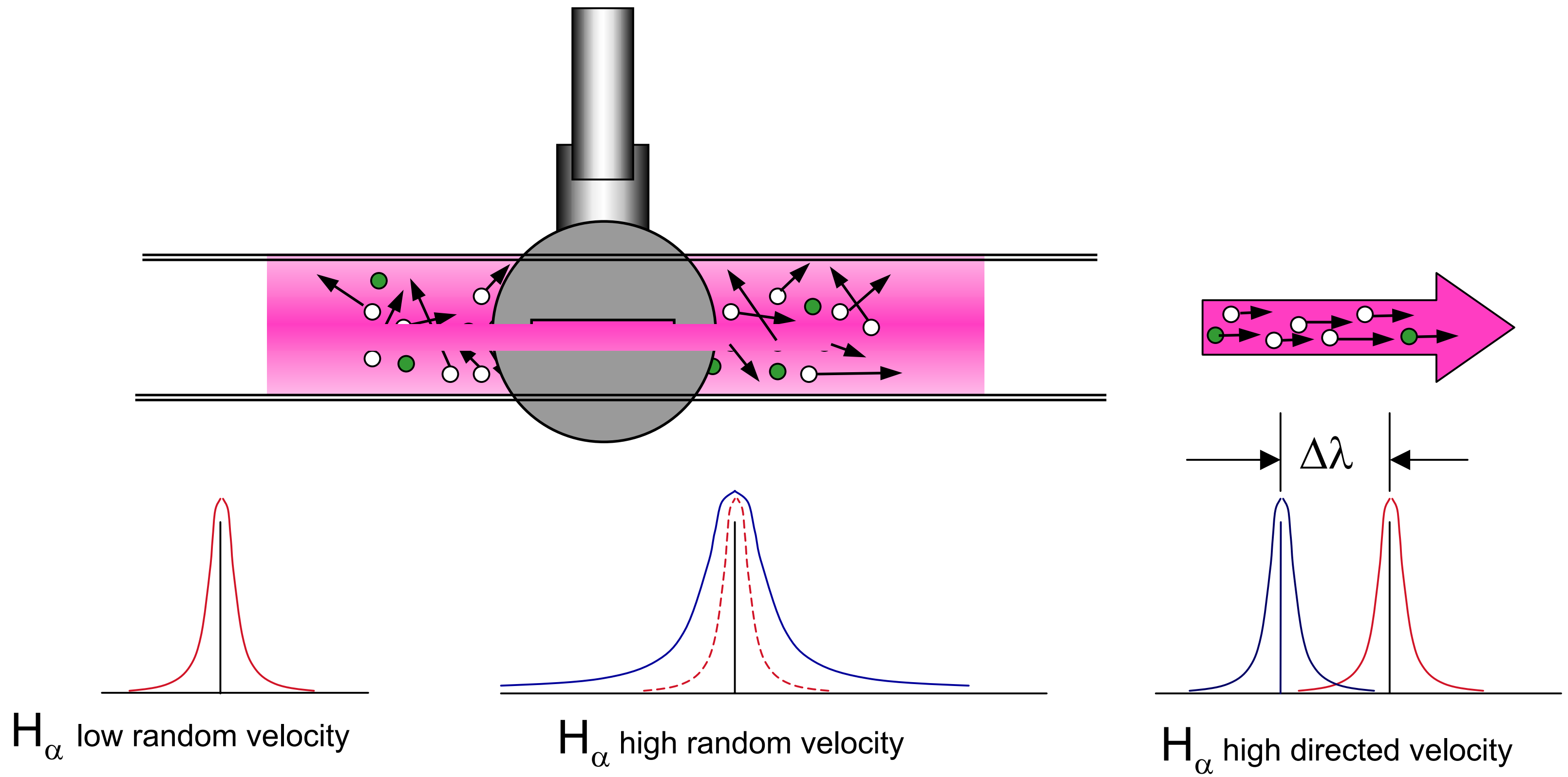
Mills (2000) suggests that the energetic hydrogen plasmas can be explained theoretically based on an alternative solution to the Schrödinger equation that permits hydrogen atoms to collapse into increased binding energy states with binding energies of:

$$E_B = \frac{13.6\text{eV}}{n^2}$$

$$n = \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \ldots, \frac{1}{p}$$

Propulsion Potential for Energetic Mixed Gas Plasma

Convert Random Translational Energy to Directed Energy

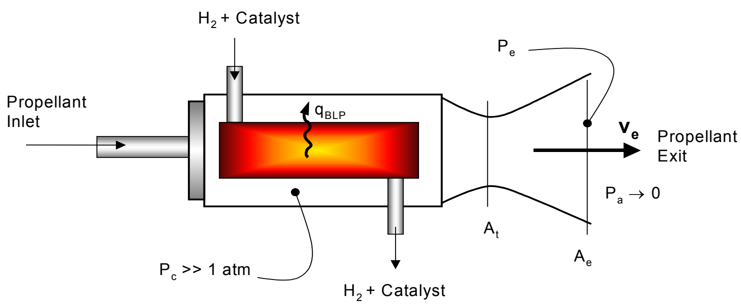


Thruster Hardware Development

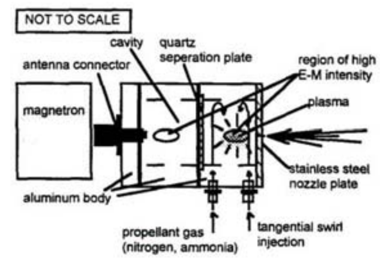
Conceptual Designs for First-Generation BlackLight Thruster

A review of the propulsion literature and comparison with the conditions under which the BlackLight Process is said to occur yielded the following promising conceptual designs BlackLight thrusters:

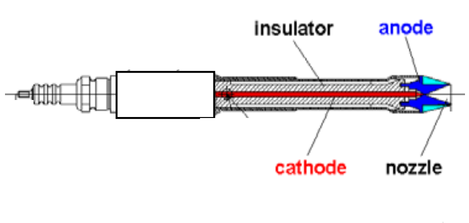
BLP Thermal Propellant Jet



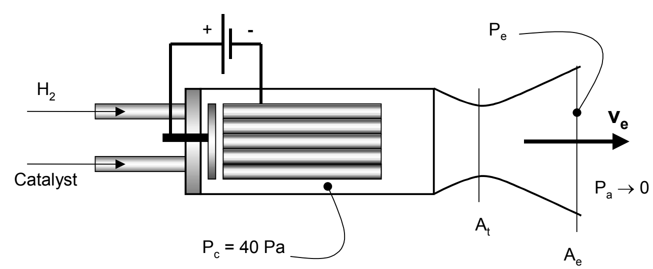
Microwave ArcJet Derivative (Micci,1999)



ArcJet Derivative (Curran, 1988)



BlackLight Plasma Thruster



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Thruster Hardware Development

BlackLight Plasma Thruster (BLPT)

A H_2/Ne compound hollow cathode gas cell was chosen as a starting point to design the first iteration BlackLight Plasma Thruster.

Disassembled H_2/Ne compound hollow cathode gas cell
(Mills, *et al*.,2002).

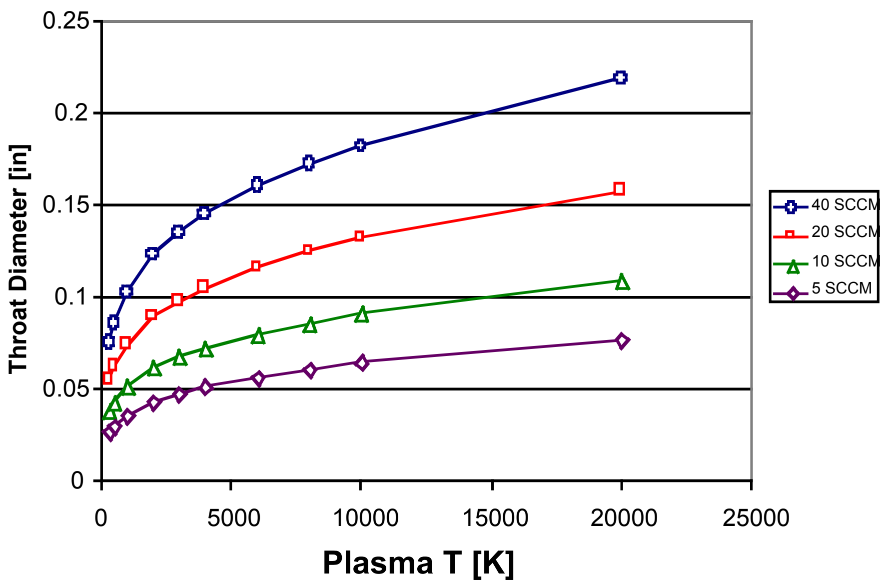
3D Solid model of BlackLight Plasma Thruster assembly

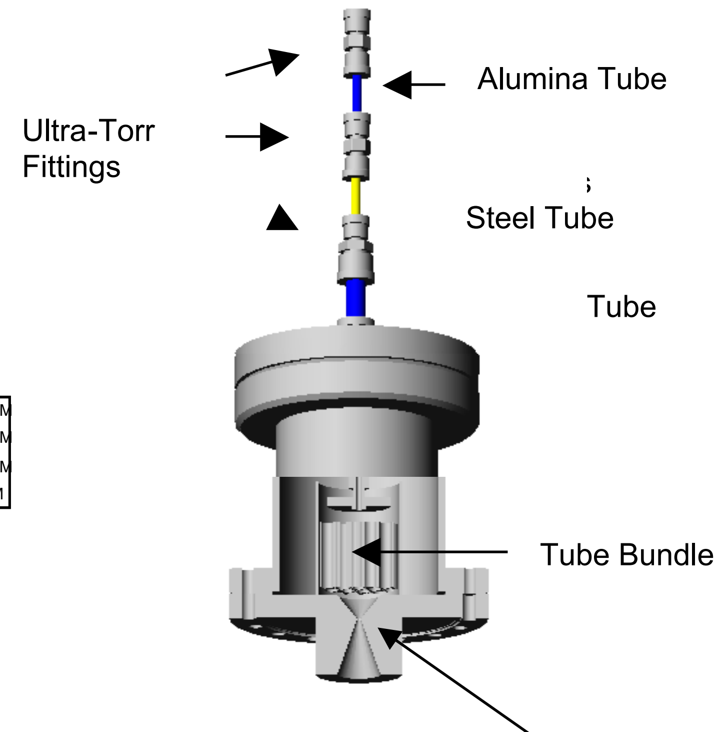
Thruster Hardware Development

BlackLight Plasma Thruster (BLPT) Nozzle Design

Thermodynamic calculations were performed using the NASA CEC code (Gordon and McBride, 1973) to parametrically design the supersonic nozzle.

Required throat diameter as a function of flow rate and plasma temperature





Supersonic Nozzle, 0.100”, 100:1

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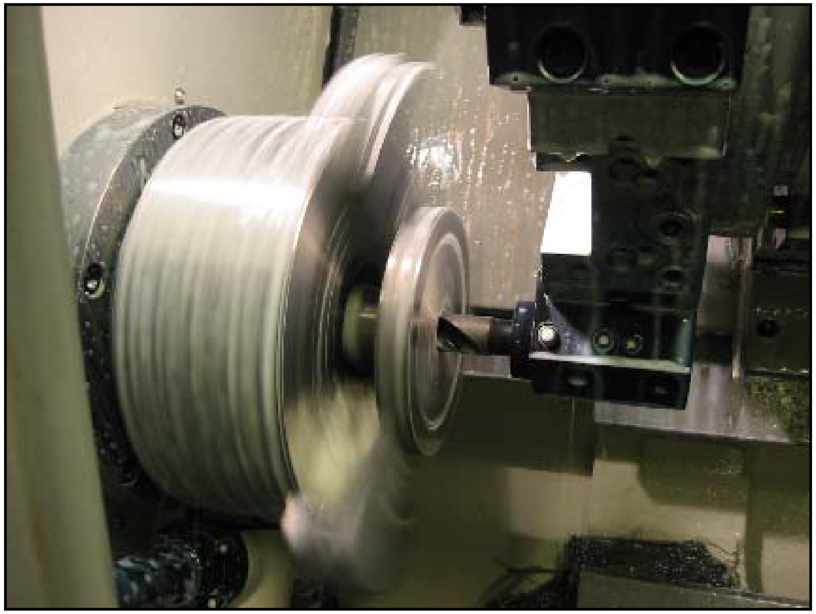
THRUSTER HARDWARE FABRICATION

BLACKLIGHT PLASMA THRUSTER (BLPT) FABRICATION

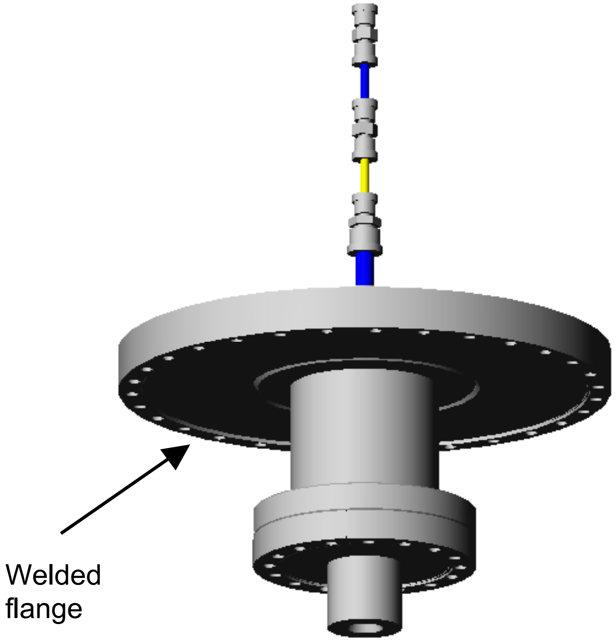
The BLPT hardware was manufactured in-house using a CNC turning center and CNC milling center. The diverging section of the 20:1 and 100:1 nozzles were machined using a wire EDM.



THRUSTER HARDWARE FABRICATION

BLACKLIGHT PLASMA THRUSTER (BLPT) FABRICATION

The thruster hardware was manufactured to adapt to a 13.25" CF vacuum flange for installation into the vacuum chamber for exhaust velocity measurement.



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THERMAL CHARACTERIZATION TESTING

BLACKLIGHT PLASMA THRUSTER (BLPT)

To better understand the thermal characteristics of the BlackLight process so that it can be optimized for the BLPT, a Ne/H_2 gas cell was instrumented with 12 high temperature type K thermocouples.

Schematic diagram of Ne/H_2 gas cell showing thermocouple locations

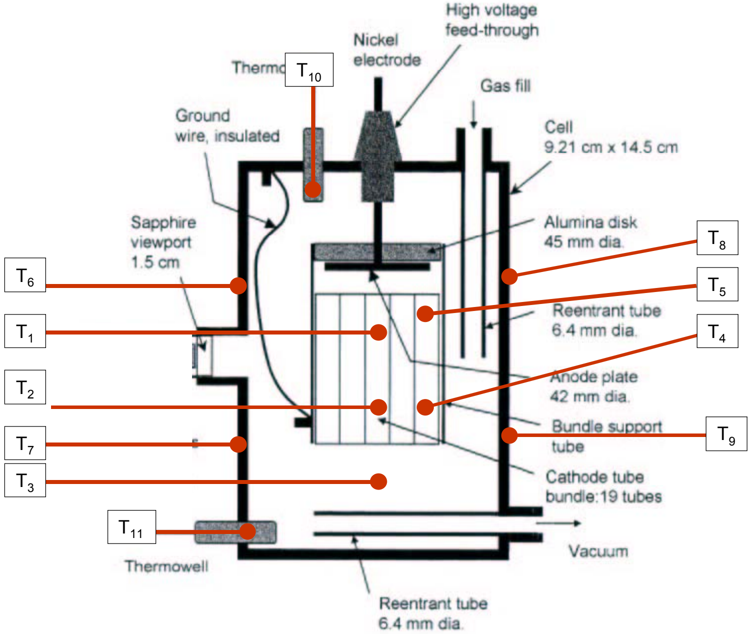
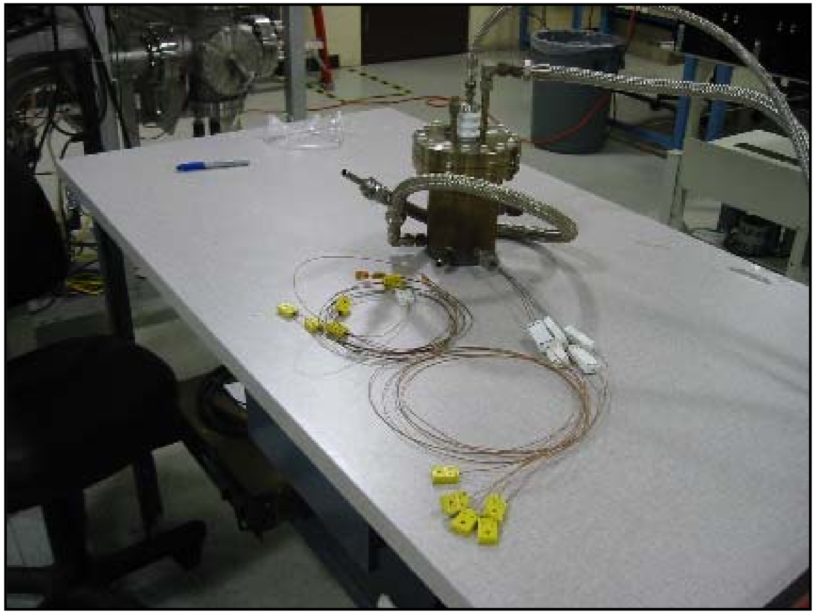


Photo of Ne/H_2 gas cell instrumented for thermal testing



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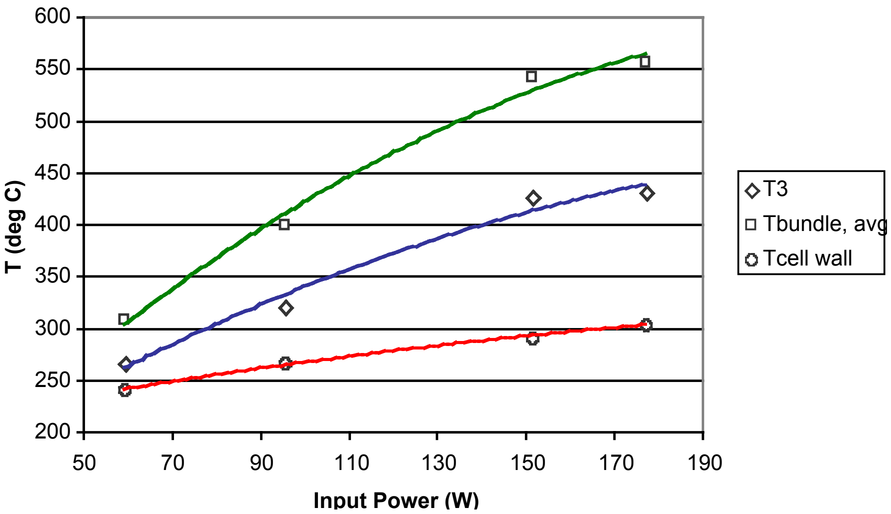
THERMAL CHARACTERIZATION TESTING

BLACKLIGHT PLASMA THRUSTER (BLPT)

The experimental system consisted of a H_2/Ne gas feed system, vacuum pump, kiln, Xantrex XFR600-2 (0-600V, 0-2A) DC power supply and PC-based data acquisition system.

Experimental setup for thermal characterization testing

Tube bundle and cell wall temperature vs. input power



THRUSTER HARDWARE DEVELOPMENT

BLACKLIGHT MICROWAVE PLASMA THRUSTER (BLMPT)

In parallel with the BLPT, a BlackLight Microwave Plasma Thruster (BLMPT) was designed based on recent developments using H_2/catalyst and H_2O microwave plasmas.

Schematic diagram of BlackLight Microwave Plasma Thruster

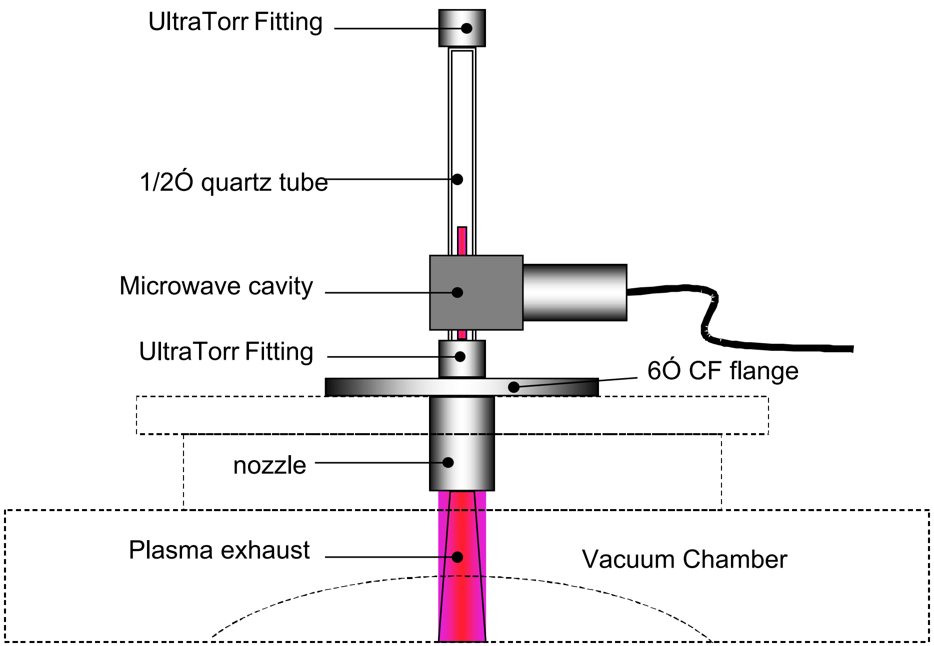
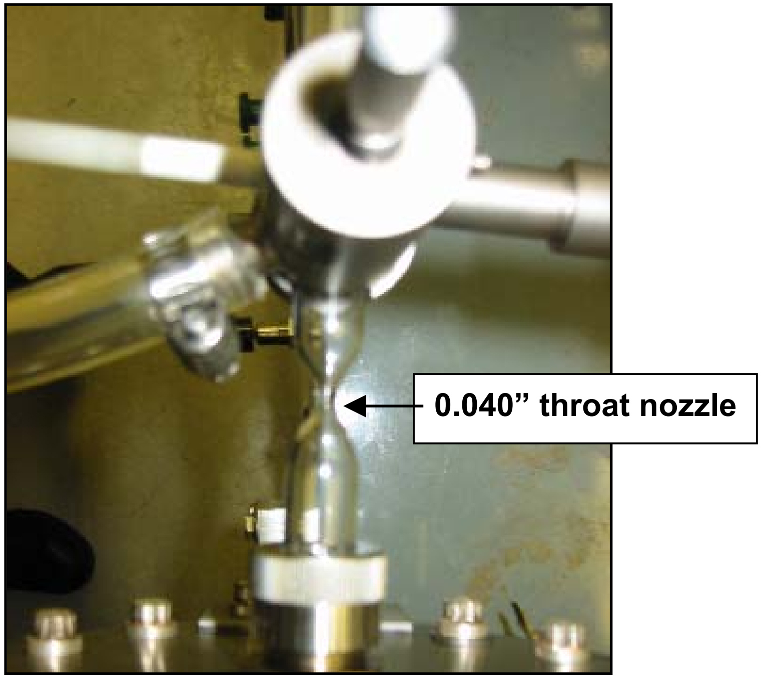


Photo of prototype microwave thruster showing quartz nozzle

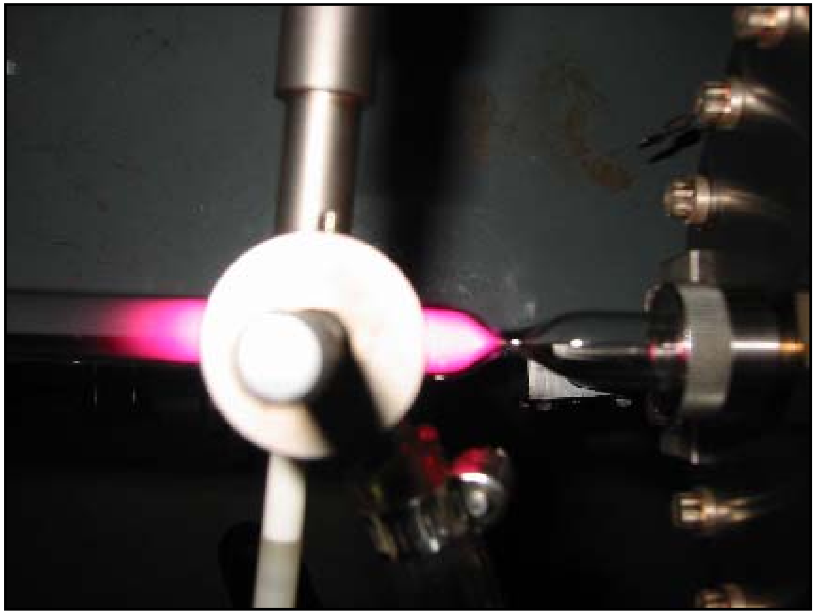


THRUSTER HARDWARE DEVELOPMENT

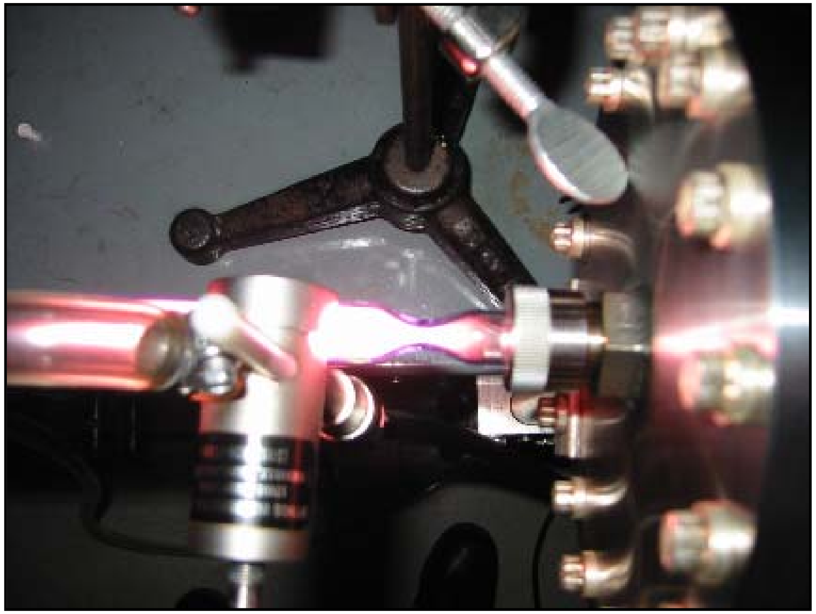
BLACKLIGHT H_2O MICROWAVE PLASMA THRUSTER (BLMPT)

To determine required throat diameter a series of experiments were conducted with varying throat diameter (0.025”, 0.050”, 0.100”, 0.200”).

0.025” Throat Diameter



0.100” Throat Diameter



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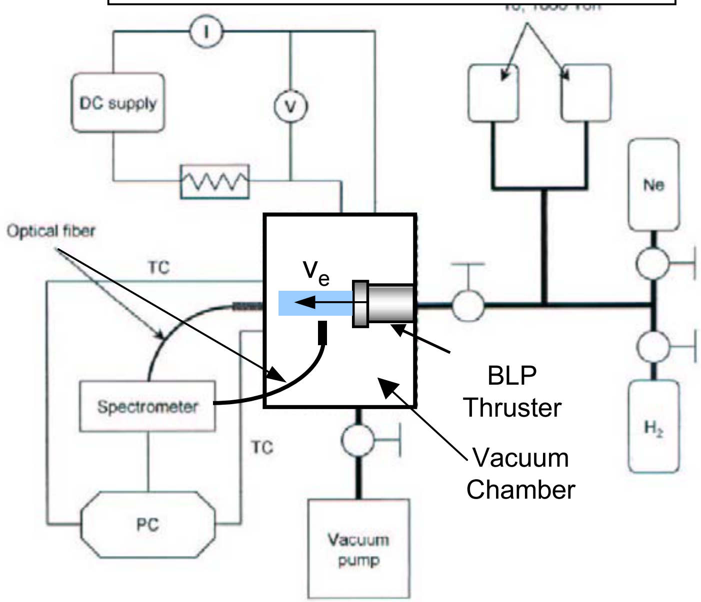
Thruster Proof-of-Concept Testing

Development of Apparatus for BLPT and BLMPT Performance Tests

- A vacuum test chamber apparatus has been developed to characterize specific impulse (I_{sp}) and overall thruster efficiency (η).
- Exhaust velocity (v_e) will be measured using a Doppler shift technique developed by Micci and co-workers (1999).

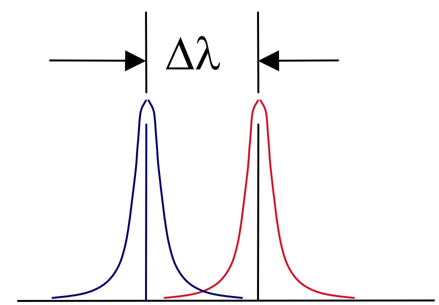
System Schematic Diagram



$$v_e = c\frac{\Delta\nu}{\nu}$$

$$I_{sp} = v_e/g_o$$

$$\eta = \frac{\dot{m}\, v_e^2}{2\dot{W}}$$



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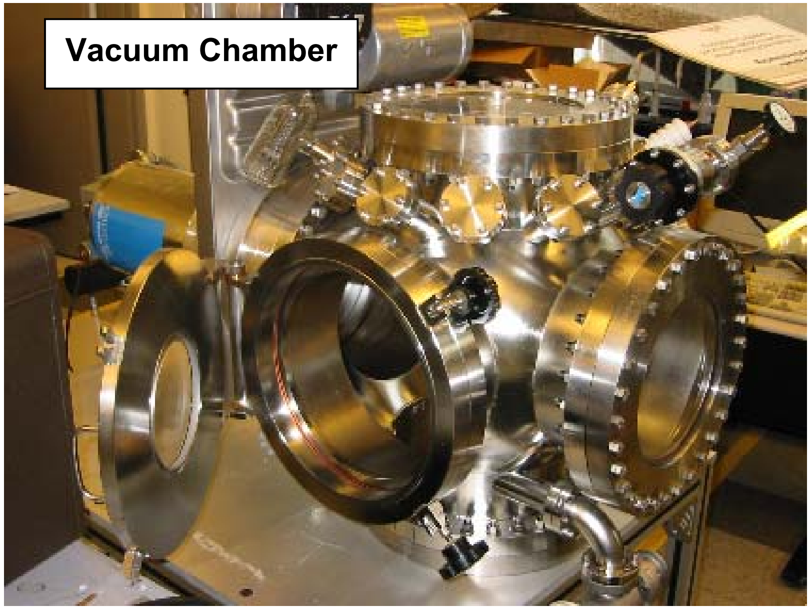
THRUSTER PROOF-OF-CONCEPT TESTING

DEVELOPMENT OF APPARATUS FOR BLPT AND BLMPT PERFORMANCE TESTS

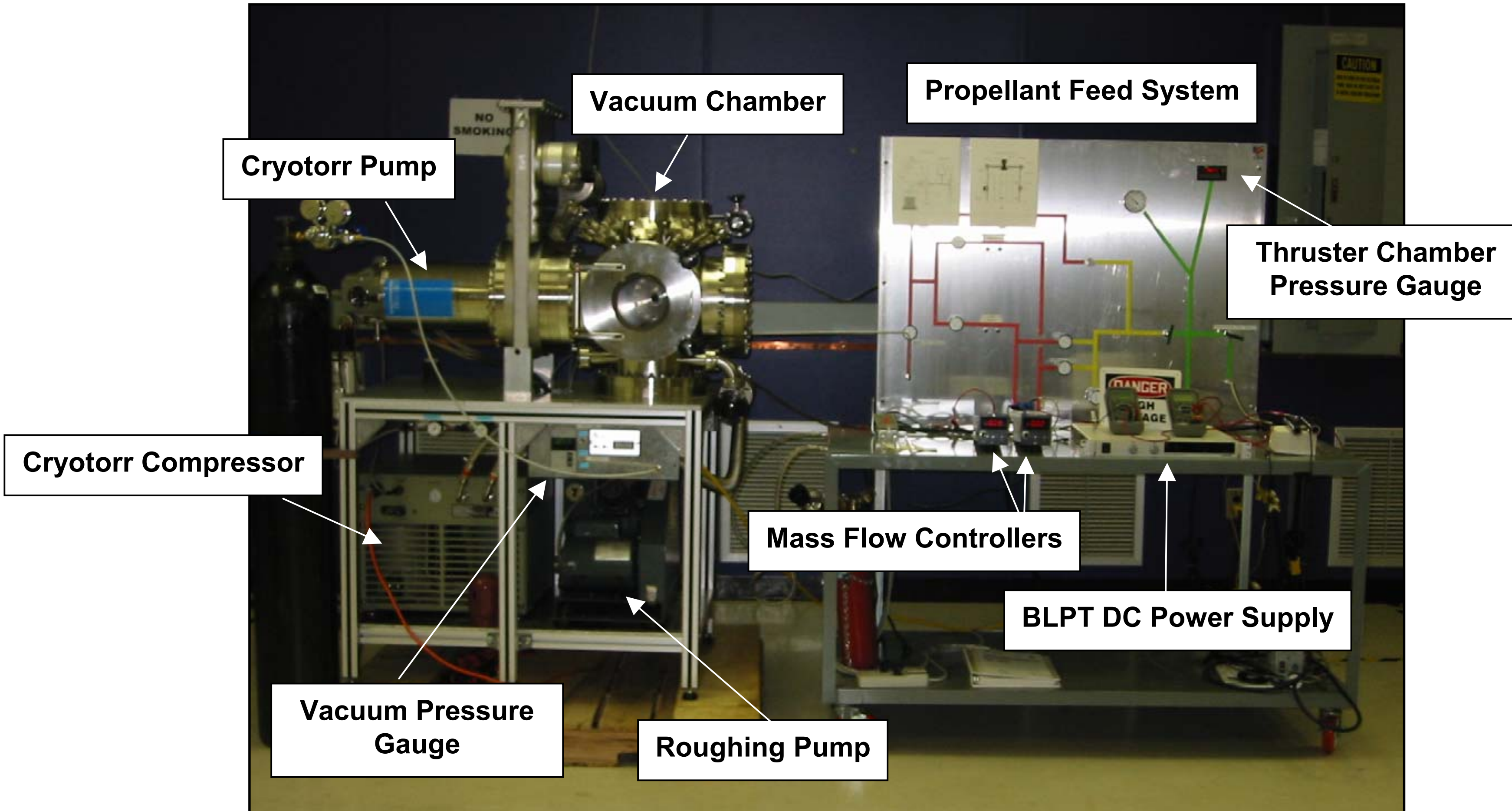
The thruster test firing will be performed in a vacuum chamber manufactured by MDC. The chamber is fitted with a CryoTorr 8 cryopump and can achieve vacuum levels of 1.0 e-7 Torr.

Doppler shift will be measured using the JY Horiba 1250M visible spectrometer, which has a wavelength resolution of 0.006 nm.



THRUSTER PROOF-OF-CONCEPT TESTING

EXPERIMENTAL SETUP FOR BLPT AND BLMPT PERFORMANCE TESTS



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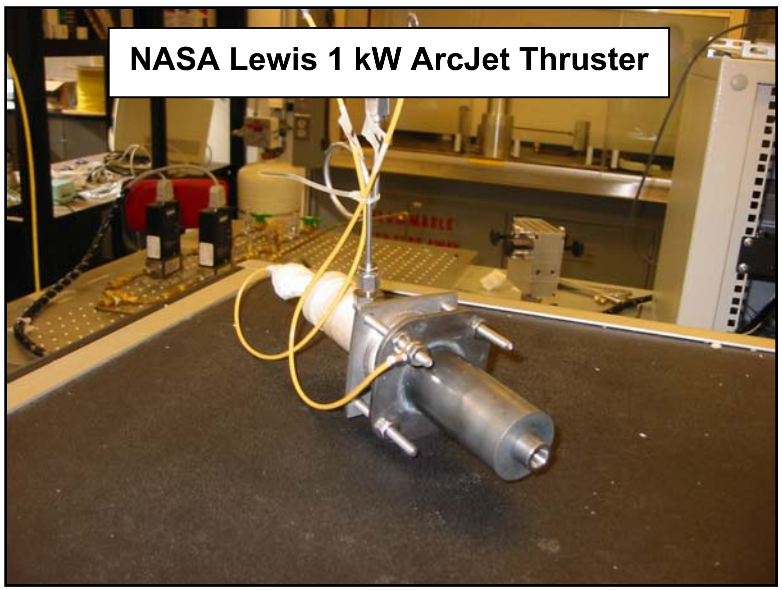
THRUSTER PROOF-OF-CONCEPT TESTING

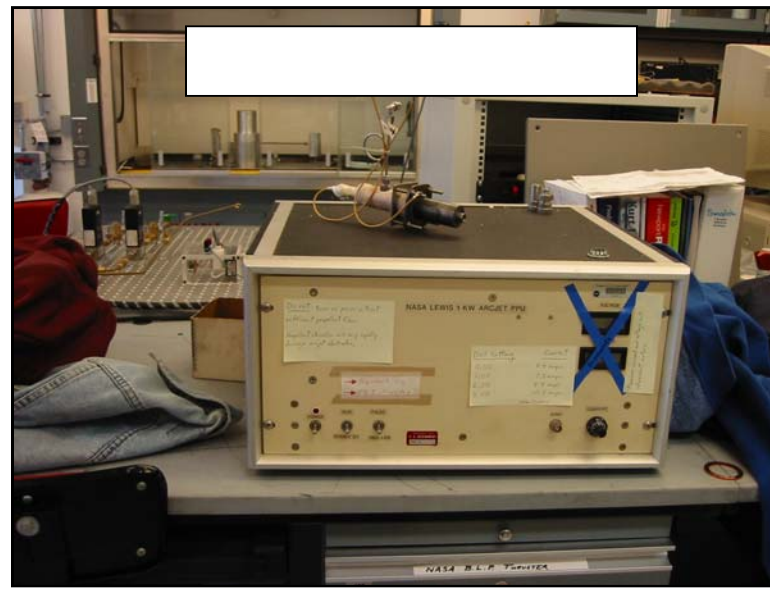
VALIDATION OF DOPPLER SHIFT EXHAUST VELOCITY MEASUREMENT

- **A NASA Lewis 1 kW class ArcJet** (Curran, *et al*., 1990) **was obtained on loan from NASA Glenn Research Center.**

- **The ArcJet, which can achieve an exhaust velocity of approximately 10,000 m/s, will be used to test our Doppler shift technique.**

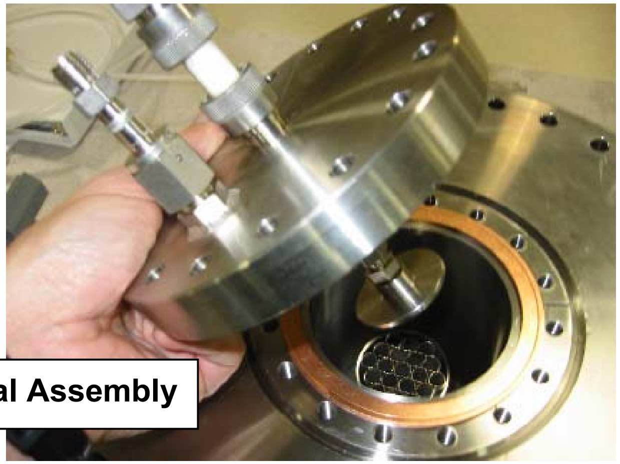


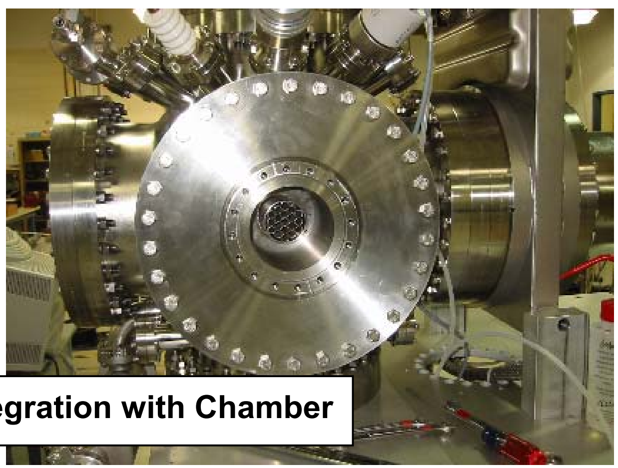
NASA Lewis 1 kW ArcJet Thruster

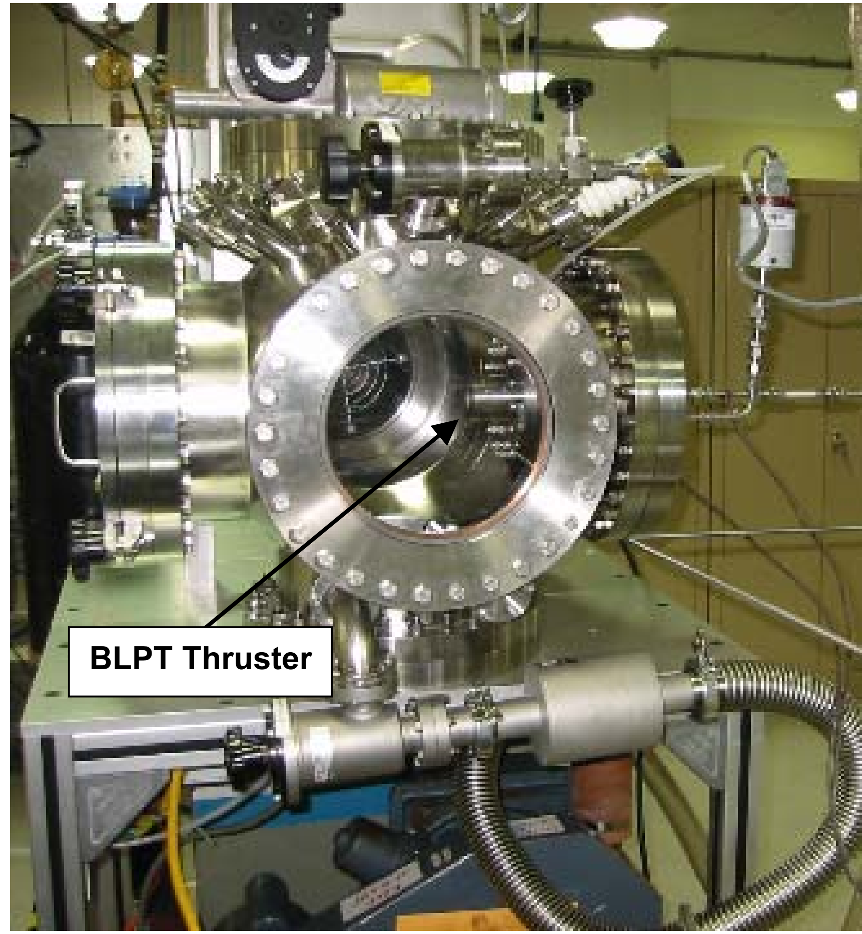


Thruster Proof-of-Concept Testing

Integration of BLPT Hardware Into Vacuum Chamber

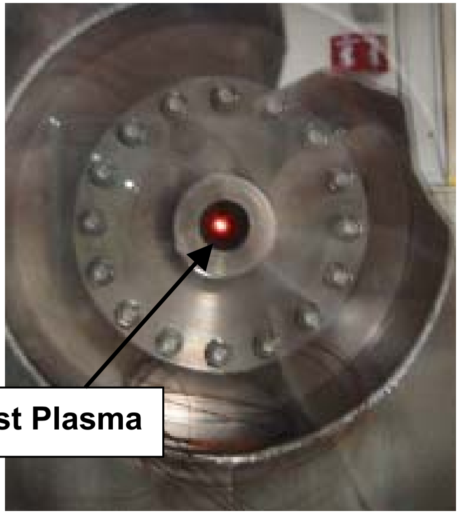






THRUSTER PROOF-OF-CONCEPT TESTING

BLPT THRUSTER FIRING IN VACUUM CHAMBER



Exhaust Plasma

Test Firing of BLPT Thruster

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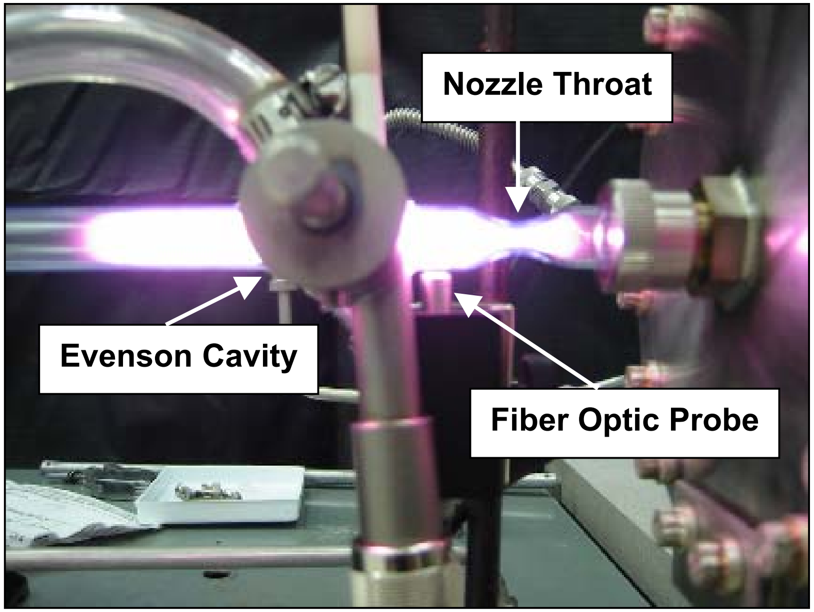
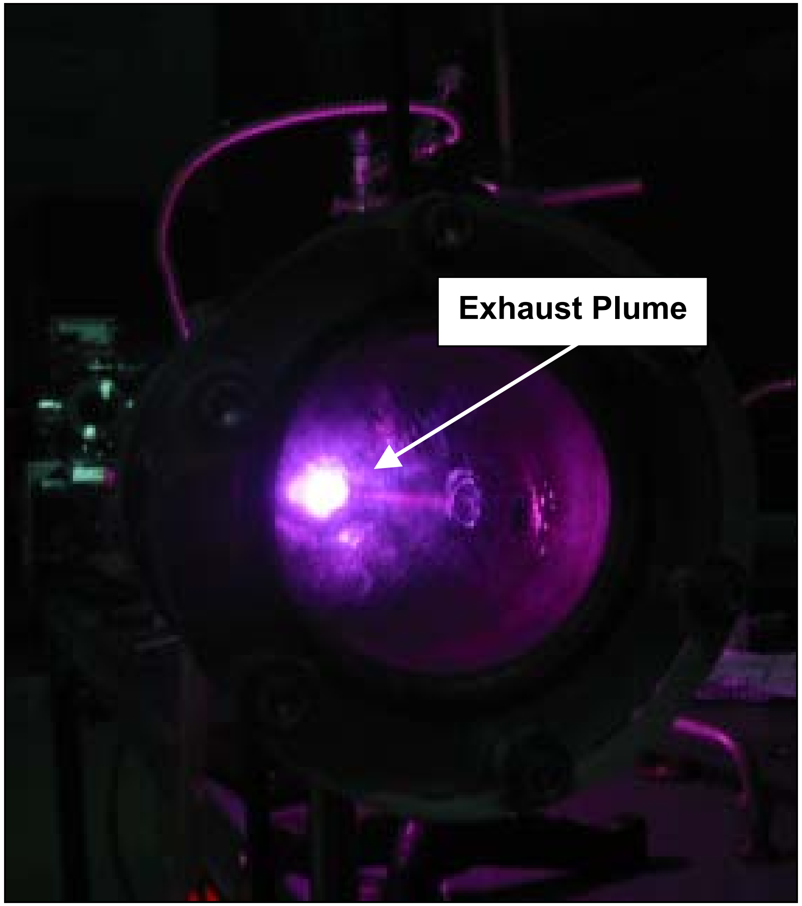
Thruster Proof-of-Concept Testing

BlackLight H_2O Microwave Thruster Firing

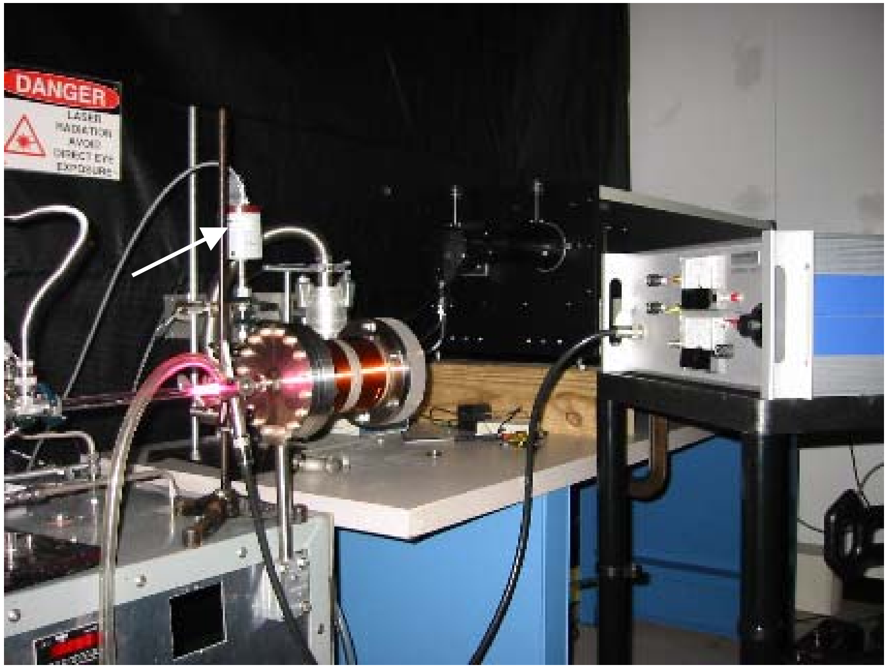




THRUSTER PROOF-OF-CONCEPT TESTING

BLACKLIGHT H_2O MICROWAVE THRUSTER FIRING

Doppler shift measurement using JY Horiba 1250 M



Tuning and positioning the Evenson Microwave Cavity

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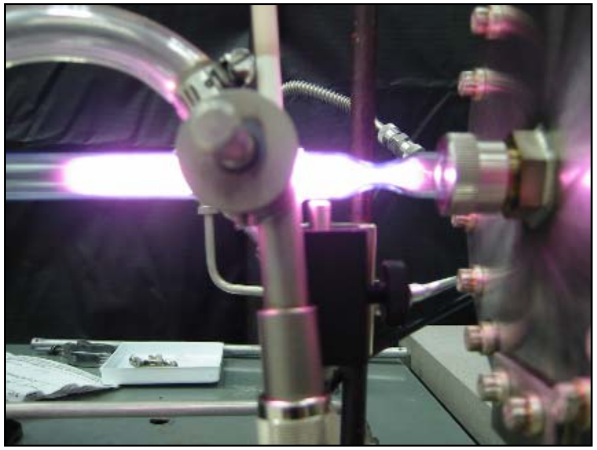
The BlackLight Rocket Engine

Summary and Ongoing Work

- Experimental results on the mixed gas hydrogen plasmas are reproducible.
- BLPT hardware complete and Doppler shift measurement is underway.
- BLMPT testing is being conducted, but additional hardware development required to install Evenson cavity inside vacuum chamber.
- More work needs to be conducted to identify alternative means to convert random energy of H atoms to directed kinetic energy.
- Potential applications for micropropulsion.



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Mike Resciniti, Peter Jansson, John Schmalzel and Mike Muhlbaier

Anthony Marchese and Chuck Linderman

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