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Status of Real-Time Laser Based Ion Engine Diagnostics at NASA Glenn Research Center

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Status of Real-Time Laser Based Ion Engine Diagnostics at NASA Glenn Research Center

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Abstract

The development status of laser based erosion diagnostics for ion engines at the NASA Glenn Research Center is discussed. The diagnostics are being developed to enhance component life-prediction capabilities. A direct measurement of the erosion product density using laser induced fluorescence (LIF) is described. Erosion diagnostics based upon evaluation of the ion dynamics are also under development, and the basic approach is presented. The planned implementation of the diagnostics is discussed.

Nomenclature

j = flux, $m^{-2}s^{-1}$
n = number density, m^{-3}
$\bar{v}$ = average velocity, m/s

Introduction

The already difficult and time-consuming task of life testing electric propulsion systems has been further complicated by the advent of highly throttleable engines like the NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) ion engine on the Deep Space 1 spacecraft. Throttling capability is a necessity for solar-powered planetary spacecraft and can enable many power-rich spacecraft to optimize their transit upon either trip time or propellant consumption [1]. Engine throttling introduces a complication to efforts to predict thruster life; the wear rates of thruster components are in general dependent upon the operating conditions. Since the time and cost required to validate life experimentally at each throttle condition are prohibitive, wear tests of the NSTAR ion engine prior to the launch of Deep Space 1 were conducted at a single throttling condition which was believed to yield the greatest component wear rates. Without *in situ* erosion diagnostics, the conditions of typical wear tests preclude collection of wear information at multiple operating conditions since post-test examination measures the integrated component wear.

Laser induced fluorescence (LIF) is a highly sensitive diagnostic that may be used to measure erosion rates in real-time. In LIF, a laser is tuned to a transition in the target species. The light excites the target neutrals or ions, and the subsequent fluorescence of the excited state is detected using some variant of monochromator. If the excited state of the target species is saturated and the plasma induced fluorescence (PIF) is much less than the LIF, then the intensity of the fluorescence is directly proportional to the density of the original (pre-excited) state. When the overwhelming majority of atoms or ions are in the ground state, and the ground state is excited by a laser, the fluorescence intensity is proportional to the species density. Laser induced fluorescence can also be used to measure the velocity of a target species. By scanning a laser near a known transition, the wavelength distribution of the fluorescence intensity is broadened based upon the species velocity distribution along the path of the laser. Consequently, LIF may be used either to directly detect the density of erosion products or, where those products are too sparse, to measure the ionic species density and velocity distribution to calculate erosion.

Laser induced fluorescence has been used previously to measure the relative wear rate of the accelerator grid in real-time and to study the discharge and beam plasmas of ion thrusters [2–4]. Other researchers have demonstrated absolute density measurement of sputtered molybdenum using LIF [5]. By measuring the density of the eroded species in the regions near the source component using LIF, the wear rate of thruster elements may be calculated. A LIF based erosion diagnostic will enable determination of component wear as a function of operating conditions. An effort is underway at the NASA Glenn Research Center to develop LIF-based density measurements to facilitate component lifetime evaluation, and this paper reviews the work being conducted.

The laser induced fluorescence of molybdenum sputtered from ion thruster accelerator grids reported in References 3 and 4 was based upon excitation of the 390.2-nm ground state molybdenum transition and monitoring the resonant fluorescence. Crofton [4] demonstrated relative density detection of molybdenum downstream of the thruster for accelerator grid voltages between 225 and 350-V below ground. Additionally, relative sensitivities to beam current and propellant utilization efficiency were also reported [4]. While these investigations demonstrated the feasibility of using LIF to detect sputtered molybdenum from the accelerator grid, neither realized the full potential of LIF as a real-time absolute erosion rate diagnostic [3,4]. Williams [2] measured the relative densities of molybdenum and tungsten downstream of the discharge cathode assembly of an NSTAR derivative 30-cm ion engine. The discharge plasma provided sufficient excitation of the erosion products to enable LIF using visible wavelength excitation [2] Since the ground state is generally the most populous and is the least susceptible to changes in electron number density and temperature, LIF density measurements which access the ground state are considered the most accurate. Researchers conducting similar studies of molybdenum erosion in fusion devices have demonstrated absolute number density measurements using LIF [5]. The work focused on the 345.64-nm ground state transition which fluoresces at 550.6-nm. The non-resonant fluorescence provides the added benefit of eliminating the effect of scattered laser light inadvertently perturbing the measurement. The NASA Glenn Research Center (GRC) is currently developing a laser induced fluorescence diagnostic based on non-resonant fluorescence to detect the absolute density of erosion products from both internal and external ion engine components to predict life.

Additionally, component lifetimes may also be estimated by measuring the ion flux to the components. The sputter rate is proportional to the ion flux and energy distribution. To compute the ion flux to a component, the density and velocity distribution must be known. As discussed previously, LIF can be used to measure the density of a species. Several researchers have also successfully measured ion velocities internal to and within the plume of electric propulsion engines [2,6,7]. By combining density and velocity data, the ion fluxes and consequently the erosion rate can be calculated. While direct measurement of the eroded species number density is expected to yield the most accurate erosion information, the technique ignores the physical mechanisms responsible for the erosion. Information regarding the physical mechanisms of component wear may enable more intelligent design solutions to alleviate erosion. Further, for components with extremely low wear rates or poor optical access, the density of eroded material may be insufficient for detection with LIF. By interrogating the bombarding ion population, the erosion can be inferred even when the component is inaccessible to the direct erosion product density measurement. Consequently, the NASA Glenn Research Center has also initiated a program to measure the ion densities and velocities near critical components using LIF. The intention is for the ion-based laser diagnostics to compliment direct measurements of the eroding species.

This paper presents the status of the NASA Glenn efforts to develop laser based diagnostics to evaluate ion engine component life. The LIF erosion product density measurement is discussed with an emphasis on the modifications employed to yield a more successful diagnostic than those previously reported. The ion-based LIF diagnostics are also discussed.

Direct Erosion Product Detection

The internal and external erosion products in an ion engine are expected to be overwhelmingly in the ground state near their source. By using LIF in this region and targeting a ground state transition, the intensity of the fluorescence is largely a function of the number density and the laser intensity. If the laser intensity is increased until saturation is achieved in the target species, then the fluorescence is dependent only upon the number density of erosion product atoms. When the plasma induced fluorescence (PIF) is comparable to LIF, the technique becomes complicated, however, under low-wear rate ion engine conditions, the PIF is usually much weaker than the LIF [3].

To utilize the LIF density measurement of the erosion products to quantify the erosion rate requires either measurement or modeling of the velocity distribution of the eroded material. While LIF is a suitable technique for measuring species' velocity distributions, the extremely low density of erosion products under ideal circumstances makes accurate velocity distribution measurements difficult to obtain. The mean velocity of sputtered molybdenum has been reported to range from 550 to 700-m/s for bombarding ion energies from threshold to 1200-eV [2,8]. Since the velocity range is relatively small for a wide range of bombarding energies, a value of 625±75-m/s for molybdenum will be adopted for the first order analysis presented here. Stuart, Wehner, and Anderson [8] report average velocities for a number of other elements of interest for electric propulsion devices.

To first order, the flux of eroded material from a thruster component can be approximated by the familiar form

$$j = \frac{1}{4} n\bar{v} \tag{1}$$

which assumes that the eroded material forms a Maxwellian distribution. By equating a known wear-rate to the Maxwellian flux from Equation 1, estimates of the density of erosion products can be calculated to establish the required detection limits. Given the first order analysis presented here and the results of the 8,200 hour wear test of the NSTAR ion engine, the number density of molybdenum atoms adjacent to the accelerator grid was calculated and is shown in Figure 1 [9]. The density produced by erosion of the accelerator grid apertures is included to indicate the level of detection necessary to differentiate the primary wear patterns on the accelerator grid. Detection of molybdenum density down to 10^{13}-m^{-3} will be sufficient for evaluation of accelerator grid life for near term engines with molybdenum optics. Accelerator grid LIF with titanium or carbon based optics will require increased sensitivity for the same beam current density. Optical access to the accelerator grid for two-grid optics is obtained relatively easily.

Conversely, optical access to the screen grid poses one of the serious challenges to the application of LIF erosion diagnostics. Additionally, the proximity of the screen grid to the accelerator grid and the extremely low erosion observed previously [10] contribute to the difficulty in measuring screen grid erosion in real-time. Direct optical access to the screen grid may be obtained via fiber optics, although the degree to which this method requires modification to the thruster may relegate its use to specialty engines [2]. The minimal optical access afforded by the fiber optics combined with the low erosion rate of the screen grid necessitate greater laser intensity than that required for the accelerator grid. Given the difficulties in obtaining a highly focused beam out of a fiber optic, laser power must increase to achieve greater intensity at the point of delivery. Finally, sputtered material from the accelerator grid apertures may obscure the screen grid erosion signal. Careful measurements of accelerator grid erosion downstream of the thruster may enable removal of the component of the LIF signal due to sputtered material from the accelerator grid apertures. These technical challenges are formidable, and the relatively minor erosion observed on the screen grid dictate that this diagnostic be developed only in the event that it becomes more necessary.

A real-time LIF discharge keeper or cathode erosion diagnostic may be implemented with slightly less complexity than that dictated by the screen grid. Williams has demonstrated LIF with both the discharge cathode and keeper with a specialty 30-cm ion engine [2]. Erosion of the discharge cathode keeper in the ongoing Extended Life Test of the NSTAR flight spare ion engine has highlighted the deficiencies of existing methods of life determination [11]. Two previous wear tests of engineering model NSTAR ion engines with a discharge cathode keeper exhibited maximum erosion rates of approximately 70-µm/khr on the downstream face [11]. The ongoing extended life test, which has been conducted at several different throttling conditions, has exhibited wholly different erosion of the discharge cathode keeper than the previous tests.

LIF Configuration

A schematic of the pulsed laser system to be used to detect erosion products is presented in Figure 2. A Nd:YAG laser pumps a dye laser with the 532-nm second harmonic. For molybdenum detection, the dye laser is operated with a 698-nm centered dye with a maximum output of 60-mJ/pulse. The dye laser is tuned to approximately 690-nm, and the output is sent to a beta barium borate (BBO) crystal where second harmonic generation yields the desired 345.64-nm beam. Part of the ultraviolet beam is sampled by a pulsed wavemeter to assist in tuning the laser. The second harmonic has been demonstrated up to 1.5 mJ/pulse with new dye. The beam is coupled into a 0.6-mm diameter core fused silica fiber optic for delivery to the vacuum chamber. This means of beam delivery provides the flexibility necessary for varied operations in VF-11 at the NASA Glenn Research Center, however, the maximum demonstrated pulse energy out of the fiber is approximately 350-µJ, indicating strong losses. Nevertheless, 350-µJ for this transition in molybdenum has been demonstrated to be sufficient for detection of number densities as low as 2.5×10^{14} m^{-3} in a fusion apparatus where temperature broadening and the Zeeman effect complicate the measurements [5]. Increased density detection sensitivity will be realized in the relatively quiescent discharge and beam plasmas of ion engines.

For molybdenum, the optical system is configured to detect fluorescence using an intensified CCD (ICCD) camera with a 10-nm bandpass interference filter centered at 550-nm. The ICCD camera is gated to collect light only during the fluorescence following the laser pulse. A TTL signal from the Q-switch is used to trigger data collection. Additionally, a photodiode is used to detect the intensity of the laser so that the strength of the fluorescence signal can be correlated to the pulse energy.

LIF Calibration

Calibration of the LIF density diagnostic is accomplished either via a reference vapor density of the target species or by a spectral radiance source [5,12]. The latter technique requires a standard spectral radiance lamp. It was believed that this instrument was insufficiently robust to be employed in an in situ calibration capacity. Conversely, a density cell made of the target species is relatively easy to implement *in situ*; the calibration cell is more resistant to the near-thruster environment than a spectral radiance lamp. Consequently, the approach using a density standard to calibrate the LIF density diagnostic was adopted.

Erosion Measurement by Bombarding Ion Dynamics Evaluation

A complimentary technique to measure ion engine component wear involving quantification of the ion flux to engine components is also being implemented at the NASA Glenn Research Center. With both the energy and composition of the bombarding ion population, the sputter erosion rate may be calculated.

Xenon LIF Velocimetry

Erosion of internal and external ion thruster surfaces is predominantly due to a combination of direct Xe II and Xe III impingement and charge-exchange Xe II bombardment. The density and velocity of each ionization state can be measured via a laser diagnostic technique. Charge-exchange ion populations may also be evaluated by measuring Xe I velocities; some charge-exchange collisions yield fast neutrals which can be detected with LIF. Laser induced fluorescence velocimetry is used to measure the Xe I and Xe II velocities. Multiple beam techniques employed in previous investigations are used to simultaneously measure multiple velocity components [13,14]. A sophisticated deconvolution model which was developed for the 605 nm Xe II transition will be modified to analyze the 834 nm Xe II LIF data [15]. The model allows direct determination of the velocity distribution without further assumptions such as Maxwellian distributions. It has been employed successfully in the data reduction of previous Xe II LIF velocimetry [2,16,17]. Sufficient spectroscopic data to employ the deconvolution technique for other XeI, XeII, and XeIII transitions are currently unknown, and a simple multiple-Gaussian fitting routine previously demonstrated on Xe II and Xe I data will be incorporated [13,14].

Xenon Ion and Neutral Density Measurements

The density of the ions bombarding thruster components can be measured using either LIF or laser interferometric techniques. Neutral and ionized xenon density may be measured using LIF in a manner similar to that described for erosion products and has been previously demonstrated [13,14,17]. Densities may also be measured by performing an interferometric measurement by exciting the same transition as the interrogation of LIF and also using a non-resonant laser line to estimate the total electron number density [18,19]. The resonant interferometric measurement yields an accurate measurement of the excited state populations of both ion and neutral species. The non-resonant measurement provides the variation in total electron density. Assuming quasineutrality, the electron density is roughly the same as the ion density. Together, the measurements provide estimates of the ion density and singly to multiply charged ion fractions. The data also enable a first-order calculation of plasma potential gradients.

Experimental Apparatus

Figure 3 shows the delivery of multiple beams to measure three components of ion velocity near the exit of the discharge cathode. The schematic includes a fourth beam to provide redundant measurement of one of the components. The incoming beams (IR) are split into parallel beams and then chopped at anti-harmonic frequencies so that the frequency-locked detection can discriminate between the fluorescence associated with each beam [2,13,15]. The fluorescence is collected and then measured using a filtered PMT.

Beam delivery for interferometry requires a separate, reference beam. Any of the beams shown in Figure 3 may be used as the interrogating beam and thus permit nearly simultaneous density and velocity measurement. The interference pattern is collected on a CCD camera [19].

A plasma cell provides a zero velocity reference for all Xe I and Xe II velocimetry [2,6,14,15]. It also functions as a benchmark for the interferometry. A direct calibration method for the absolute plasma density has yet to be developed, and a spectral radiance lamp is currently used to calibrate the collection optics [5].

Summary

The work being conducted at the NASA Glenn Research Center to develop real-time erosion diagnostics for ion engines was reported. Laser induced fluorescence is being developed to measure the density of erosion products in the discharge and beam plasmas. The density measurements will be used to predict component erosion and service life. Additionally, LIF and laser interferometric diagnostics are under development to quantify the ion energy and flux to the ion engine electrodes as an complimentary means to determine the erosion rate due to sputtering. The diagnostics will enable life prediction to greater accuracy than is currently available and will reduce thruster development costs by facilitating design improvements to increase service life.

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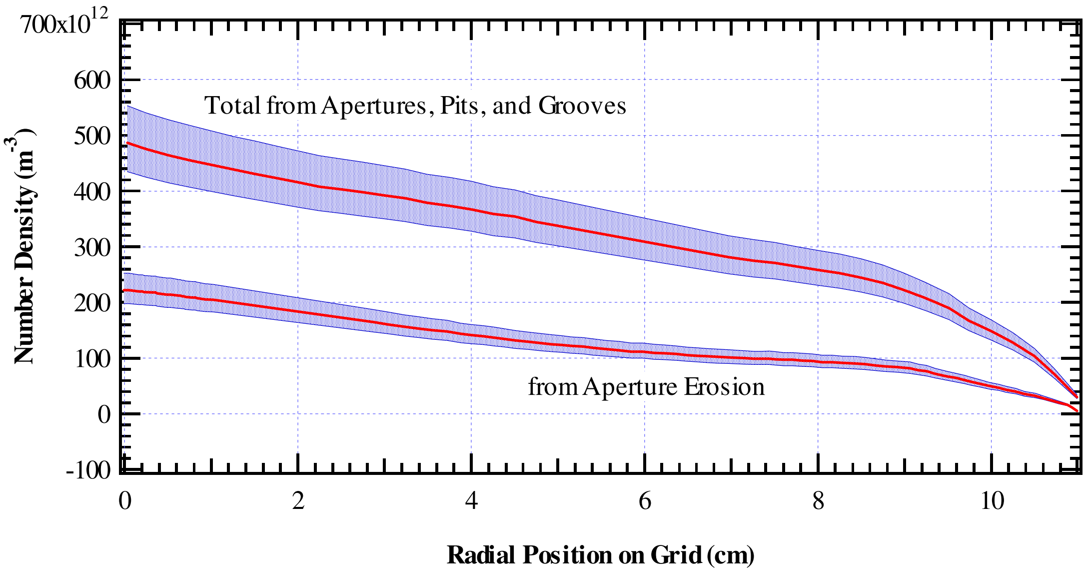

Figure 1 – Calculated ranges of density of molybdenum adjacent to the downstream face of the accelerator grid in the 8,200-hour wear test [9].

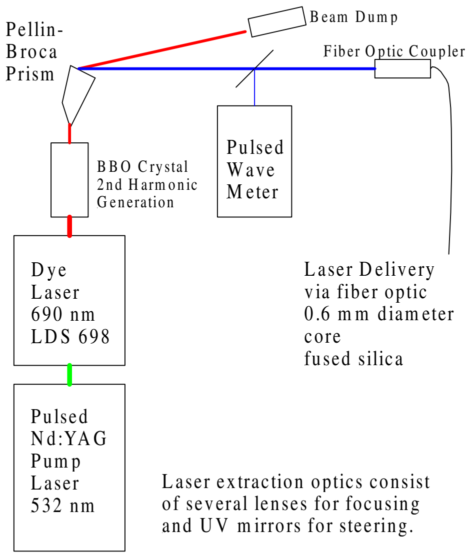

Figure 2 – Schematic of the pulsed laser system.

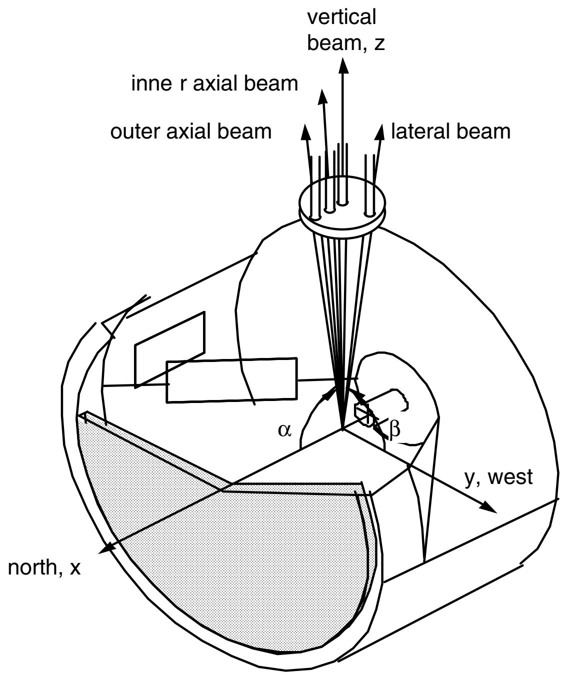

Figure 3 – Schematic of laser beam delivery. Note the location of the beams on the lens. The same beam configuration can be used for both internal and external (beam) velocimetry.

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13. ABSTRACT *(Maximum 200 words)*

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