AVS PROPULSION DIAGNOSTICS: A NEW DIAGNOSTIC DEVICE FOR NON-INVASIVE ION THRUSTER PERFORMANCE CHARACTERISATION

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KEYWORDS: AIV issues and tools (facilities diagnostics, methodologies), Spacecraft propulsion, Electric Propulsion, ion thrusters, plasma, excitation, fluorescence, Beam Induced Fluorescence, in-orbit diagnostics.

ABSTRACT:

AVS-led projects are advancing the development of non-invasive diagnostic technology for Electric Propulsion (EP) thrusters. Such technology will gain importance as EP becomes an increasingly prevalent form of spacecraft propulsion. It is expected that future development will enable marketable products by early next decade.

As such, the Beam Induced Fluorescence method has been assessed for its applicability to non-invasive diagnostics for EP. The concept was proved feasible by the ‘BIFEP’ project (a joint collaboration with Surrey Space Centre and support of the UK Space Agency). A further development called ‘ORBITA’ in collaboration with ESA will provide valuable datasets of performance parameters during operation of high power EP systems in-orbit and on-board the spacecraft.

1. INTRODUCTION

Provision of reliable Electric Propulsion (EP) diagnostics enables feedback on thruster performance, fine-tuning of operational parameters, and identification of problems such as thruster component erosion or sputtering. Such knowledge leads to enhanced thruster performance and life expectancy.

Despite this, no current diagnostic method combines these features into a tightly packaged solution utilising Commercial-Off-The-Shelf (COTS) components; that is able to rapidly acquire macroscopic profiles of the thruster plume in high resolution, and with adaptability to different thruster types / test facilities / integration options.

Current state-of-the-art is considered in terms of both:

- General plasma diagnostic techniques, demonstrated on-ground
- Plasma diagnostic techniques, demonstrated in-orbit

General plasma diagnostic techniques demonstrated on-ground consist of a number of methods that may be categorised in one of four categories: Active spectroscopy, Passive spectroscopy, Optical effects from electrons, and Electrostatic probes. Examples of each are given in Tab. 1. Most of these techniques have heritage of being tested on either Gridded Ion Engine (GIE) or Hall Effect (HET) thrusters. It is noteworthy that only the electrostatic probes are ‘intrusive’ i.e. they physically intrude into the thruster plume, all other techniques are ‘non-intrusive’ on account that they are optically based and hence do not physically intrude the thruster plume.

<table>
<thead>
<tr>
<th>Diagnostic category</th>
<th>Techniques</th>
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| Active spectroscopy | - Laser Absorption Spectroscopy (LAS)  
- Laser Induced Fluorescence (LIF)  
- Two-photon Absorption Laser Induced Fluorescence (TALIF) |
| Passive spectroscopy | - Beam Induced Fluorescence (BIF)  
- Fabry-Perot Interferometry (FPI)  
- Optical Emission Spectroscopy (OES) |
| Optical effects from free electrons | - Laser Thomson Scattering (LTS) |
| Electrostatic probes | - Langmuir Probe  
- Retarding Potential Analyser (RPA)  
- Faraday Probe  
- EXB Probe  
- Emissive Probe |

Demonstrated in-orbit plasma diagnostic techniques consist of a much smaller number of methods that may be categorised as either Spectrographic cameras (i.e. OES) or Electrostatic probes. Examples of the missions on which these techniques have been used are given in Tab. 2.
It should be noted that whilst each of the examples given in Tab. 2 was a true in-orbit diagnostic, their aims were largely to monitor effects on the spacecraft due to the operation of its EP, rather than to monitor properties of the EP plume itself for the purpose of thruster performance feedback / fine-tuning. As such they do not represent EP diagnostic capabilities equivalent to that expected of the AVS-led developments.

In this paper we present results of the work that has been conducted for the BIFEP project, including simulation results and preliminary hardware design. We also discuss the ongoing work of the ORBITA project in collaboration with ESA that aims to develop an in-orbit EP diagnostic system.

### 2. BIFEP

The BIF method relies on the excitation and subsequent fluorescence of background residual gas by the ion thruster under test in a vacuum chamber [1, 2]. Properties such as wavelength and intensity of the emitted light provide valuable insight into the density and energy of the ion distribution in the thruster plume and hence performance metrics of the thruster. BIFEP (a Beam Induced Fluorescence diagnostic device for EP thrusters) investigated the application of this technique to EP.

BIFEP has improved understanding of certain Assembly, Integration and Verification (AIV) issues such as the need to provide diagnostic verification across specific ranges of ion energy, ion beam current density and / or beam divergence; each of which varies according to thruster type. In addition, preliminary designs have been developed for a tool that can be installed at ground-based facilities to enable rapid acquisition of thruster plume profiles during test phases. By monitoring the beam emission properties during the thruster lifetime, the diagnostic system will allow identification of deviations from a reference benchmark, symptomatic of possible nonconformities such as grid erosion or sputtering.

#### 2.1. Model of collisional / excitation processes

A general theoretical model was developed by AVS based on data obtained from the Stopping and Range of Ions in Matter (SRIM) database, followed by a more specific model incorporating cross sections [3, 4] provided by the project partners, Surrey Space Centre (SSC), of collision processes specific to EP thrusters. These models confirmed that ions of the species and energy expected from EP thrusters will cause fluorescence in a residual gas and that as either ion energy or residual gas pressure are increased, so does the fluorescence flux. In addition, the contributions made by specific collision processes to the total fluorescence flux were quantified, with the collisions of electrons with the residual gas shown to produce the greatest contribution.

An additional collisional-radiative model (CRM) was implemented by SSC. This model is based on published literature [3, 5] and accounts only for Xenon species. Results of the model show that the intensity of spectral lines in the visible range (400-700 nm) is much lower than that of those in the near-infrared range (700-1000 nm), see Fig. 1. Consequently, the BIFEP system was designed to have a high responsivity in order to be capable of detecting the lower intensity lines in the visible region.

![Figure 1 – Normalised spectrum at beam energy E/q = 200 eV for electron temperature 10 eV](image-url)

The analysis has been focused on the contributions of electron-neutral, ion-neutral, and double charge ion-neutral collisions to the overall intensity of a set of emission lines. An example of this analysis is given in Fig. 2 where comparison is made of the near-infrared (NIR) lines at three ion energies indicative of three thruster types under consideration: $E/q = 100$ eV is indicative of the Quad Confinement Thruster (QCT), $E/q = 300$ eV the HET, and $E/q = 900$ eV the GIE. The emission lines have also been matched to corresponding plasma quantities; namely those emission lines in the visible region provide information on the spatial profile of electron and ion densities, whilst intensity ratios of those in the near-infrared region allow the electron temperature to be investigated.

### Table 2 – Examples of demonstrated in-orbit plasma diagnostic techniques

<table>
<thead>
<tr>
<th>Techniques</th>
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<tbody>
<tr>
<td>OES</td>
<td>SEPAC on NASA Shuttle missions</td>
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<tr>
<td>Langmuir</td>
<td>SMART-1 (ESA)</td>
</tr>
<tr>
<td>Probe</td>
<td>ARTEMIS IPDS (ESA)</td>
</tr>
<tr>
<td>RPA</td>
<td>STENTOR PDP (CNES)</td>
</tr>
<tr>
<td>Faraday Probe</td>
<td>Express A2/A3 (Russia)</td>
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</tbody>
</table>

- $N_{\text{OES}}$: OES on NASA Shuttle missions
- $N_{\text{Langmuir Probe}}$: SMART-1 (ESA)
- $N_{\text{RPA}}$: ARTEMIS IPDS (ESA)
- $N_{\text{Faraday Probe}}$: Express A2/A3 (Russia)
Figure 2 – Intensity of NIR lines normalised to intensity lines of Xe$^+$ ions, for electrons @ $T_e = 5$ eV (top) and doubly-charged ions Xe$^{2+}$ (bottom) for various ion beam energies

2.2. Preliminary system design

Requirements on detector sensitivity were approximated by calculation of the number of photons expected to enter the detector, with the worst case estimated to be on the order of $10^4$ photons / second, and the best case on the order of $10^{10}$ photons / second. Neither of these limits is beyond the capabilities of current detection technology, for example photomultiplier (PMT) detectors have a high responsivity [6] and are capable of detecting single photons. Spectral resolution required is <0.1 nm for detection of emission lines in the visible range and ~0.1 nm for detection in the near-infrared range. Further technical design requirements identified included the need for a flexible design able to be adapted to suit the plume characteristics of the Quad Confinement Thruster (QCT), HET and GIE type thrusters; and ability to sweep the plume width to allow the spatial profiling of electron and ion densities.

Preliminary CAD drawings were produced by AVS UK based on an example hardware selection incorporating viewport, lens, spectrograph, MCP (image intensifier) and CCD, see Fig. 3.

Figure 3 – Hardware for a CCD based system: CCD (red), MCP (purple), spectrograph (black), lens (grey)

Feasibility of system integration with the Daedalus chamber at SSC, see Fig. 4, was assessed and determined to be satisfactory. Positioning of the BIFEP system in respect to the vacuum chamber and thruster plumes is shown in Fig. 5, where the yellow plume is representative of a QCT and the green plume of a GIE thruster.

Key design choices to be made during future detailed system design include the choice of specific detector hardware (PMT, spectrometer / CCD etc.) taking into account the intensity spectrum reaching the detector, given by Eq. 1; and the method of sweeping the full plume width (translation, rotation of optics etc.) in order to provide spatial information. In addition a number of technical challenges need to be addressed including expansion of the range of operation to include future planned high power EP thrusters [7, 8].

Figure 4 – Daedalus vacuum chamber facility at SSC

The intensity spectrum $S(\lambda)$ reaching the detector taking into account the effect of filters, lenses, screens, and the effect of the incidence angle of the incoming light is given by:

$$S(\lambda) = F(\lambda)S_{e,scat}(\lambda)N_e(\lambda)S_{source}(\lambda) \quad \text{Eq. 1}$$

where $F(\lambda)$ accounts for the transmission of light through the filter, $S_{e,scat}(\lambda)$ accounts for the losses due to scattering along the path in the optical system, $N_e(\lambda)$ quantifies the noise along the optical path, and $S_{source}(\lambda)$ is the intensity spectrum emitted from the plasma that reaches the optical system.
3. ORBITA

ORBITA represents the next step in diagnostic systems developed by AVS, with a goal to develop a commercially available system for testing and monitoring of EP systems by early next decade. We are investigating several techniques to monitor the plasma conditions in the plume of GIE and HET thrusters, which could be deployed for both ground tests and in-flight. The current phase of development will result in the manufacture of a breadboard model for functional validation in a laboratory environment.

The ultimate aim of reliable diagnostics is to monitor EP devices to improve the efficiency and lifetime of those devices. A number of different techniques have been used to study the performance of these types of thrusters in lab-type settings, see Tab. 1, but a widely available in-orbit solution has yet to be made. This is important, as the plasma plume of EP thrusters behave differently in space than in the higher residual gas pressure of ground based vacuum chambers.

Some space missions have monitored the performance of their ion thrusters in orbit, see Tab. 2, but these have been limited to technical demonstration and science missions as opposed to commercial platforms. These missions have also used monitoring techniques that require electrostatic probes, which disturb the thruster exhaust and may impede on the performance of the thruster.

3.1. Concept

As discussed previously, plasma diagnostics largely fall into four categories. We have begun investigating and developing a system which relies on both active and passive spectroscopy. Currently, it is the intention to develop a system that benefits from the complementarity of the two diagnostic categories. We propose that a ground based test suite could be designed which uses either LIF or LAS to study the thruster exhaust in detail in ground based tests, whist an in-orbit version of the system would rely on passively measuring the spectral emission of the exhaust using OES or FPI. In addition, the in-orbit version would be usable on-ground alongside the more sophisticated ground based test suite, allowing a direct comparison to be made between thruster performance in a vacuum chamber vs the hard vacuum of space.

3.2. Ground based test suite

The ground based system will utilise active spectroscopy to study the performance of a thruster inside a vacuum chamber. For example, a laser can be used to induce fluorescence in the xenon ions which are accelerated by the thruster, and the resulting spectral emission can be measured using a spectroscope or interferometer. The spectral fingerprint of the Xenon 1+ and 2+ ions is known, and as such the Doppler shift of the ions, which gives the exhaust velocity of the thruster, can be measured [9]. The intensity of the light can be used in conjunction with a fluorescence model to determine the number densities of the ion species. The number densities could then be used to predict the propellant flow rates, thrust and efficiency of the thruster system.

3.3. In-orbit system

A separate system for in-flight diagnostics that will rely on a simple Fabry-Perot interferometer or optical spectrometer is also being investigated. This approach is being taken for a number of reasons including the feasibility of integration on-board spacecraft and the opportunity to quantify the effect on EP performance of operation in hard vacuum vs vacuum chamber.

A spectrometer or interferometer could measure the velocity distribution of ions in the plasma plume [10], allowing for measurements of the Doppler shift and thus the exhaust velocity of the plasma plume. In addition, if a sufficient model of the emission of the plasma can be developed it may also be possible to measure the number densities of the ions in the plume. This method would not be as accurate as using LIF or LAS, as it would have lower signal-to-noise, but may prove sufficient to allow for the monitoring of thruster conditions in-orbit. The benefits of this monitoring being more accurate usage of propellant, improving predictions on how a thruster manoeuvre has affected the orbit of a spacecraft and optimising the lifetime of the thruster.

4. CONCLUSION

AVS-led projects that are advancing the development of non-invasive diagnostic technology for EP thrusters have been discussed. BIFEP proved that a concept for a ground based EP plume diagnostic system using the BIF technique was feasible. Specifically it was shown
that the concept could provide information on a number of parameters of a thruster plume, namely:

- Energy, density, and distribution of ions
- Temperature, density, and distribution of electrons

The current phase of ORBITA development will result in the manufacture of a breadboard model for functional validation in a laboratory environment, representing Technology Readiness Level (TRL) 4. This breadboard will either be designed such that it can operate both on-ground and in-orbit, or alternatively two separate variants will be designed to suit the two operational environments. The current proposition is for an active technique such as LIF or LAS to be utilised on-ground whilst a passive technique such as FPI or OEM is utilised in-orbit. These selections are subject to change as a result of an ongoing trade-off and requirement specification, however it is expected that as a minimum the system will provide information on the following thruster plume parameters:

- Velocity, temperature, density, and distribution of ions
- Other plume measurement parameters to be determined

5. ACKNOWLEDGEMENTS

Work on the two aforementioned projects has been carried out with funding assistance provided by the UK Space Agency (UKSA) and the European Space Agency (ESA) respectively.

6. REFERENCES


