# Life Estimation of Hall Thrusters Using Multi Spectral Imaging

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Harshit Gole[1]
*Liquid Propulsion Systems Centre, ISRO, Trivandrum, Kerala, 695547, India*

Umesh R Kadhane[2], Keerthy Sasidharan[3], Srinivasa Raju[4]
*Indian Institute of Space Science and Technology, Trivandrum, Kerala, 695547, India*

Shwetank Singh[5]
*U R Rao Satellite Centre, ISRO, Bengaluru, Karnataka, 560017, India*

*and*

Vijayan Nandalan[6]
*Former Group Head , Liquid Propulsion Systems Centre, ISRO, Trivandrum, Kerala, 695547, India*

**Abstract: Electric propulsion systems are increasingly used in satellites in view of its obvious advantages over the chemical propulsion system. Availability of very high specific impulse (Isp) enable the satellite to carry more useful payload and also to have more orbit life. The useful operational life of a Hall Thruster is decided based on the erosion of the ceramic liner used in the thruster. The erosion is caused due to the impingement of high energy ions. Diagnosis and analysis of temporal and spatial dynamics of plasma plume have turned out to be handy tool for determining the erosion rate of the ceramic liner on very long time scales. In this work, we propose and validate a unique method for a real time monitoring of ceramic liner erosion. The variation in the intensity of constituents of the ceramic liner have been measured in the plasma plume outside the thruster exit using Multi Spectral Imaging (MSI) instrument, by which it is possible to characterize and quantify the erosion process. In the present work, the plasma emission from the Xe species and ceramic species are separately recorded on a CMOS camera with different wavelength filters. The erosion mechanism and erosion rate of the ceramic liner is studied at different operating parameters of the thrusters such as magnetic field strength, xenon flow rate through anode & cathode, and operating voltages. Long hours of firing are called for to collect meaningful data. The angular distribution of the plasma is also studied using the recorded images. The 2-D imaging in this work can be used to find the asymmetry in the plume near the exit in Hall Thrusters.**

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[1] Project Manager, High Thrust Electric Propulsion Project (harshtgole25@gmail.com)
[2] Associate Professor, Physics Department (rkumesh@gmail.com)
[3] Research Assistant, Physics Department
[4] Research Associate, Physics Department
[5] Scientist/Engineer, Power Systems Group
[6] Former Employee, Liquid Propulsion Systems Centre, ISRO, Trivandrum

## Nomenclature

$\sigma_{en}$ = Effective electron-neutral scattering cross-section
$T_{eV}$ = Electron temperature

## I. Introduction and Background

This paper has come up with a unique methodology for the real time analysis of erosion using Optical Emission Spectroscopy (OES) technique. Erosion diagnosis and the measurement of lifetime of the ceramic liner in HETs is a demanding research area in the field of electric propulsion. Till date people have been struggling with methods which are quite time consuming, expensive and requires workforce as well. Thousands of hours are spent on testing these thrusters in order to determine its' lifetime. Several tests have been carried out for the entire duration over which the ceramic liner lasted in an attempt to predict the lifetime of thruster. Different methods are adopted for erosion measurements, which include either in-situ measurement or semi-empirical estimations. In-situ measurements which include weight loss and multilayer coating chip erosion are attempted at the cost of long firing time. In semi-empirical methods the erosion rates and yields in certain restricted experimental conditions are measured as accurately as possible and with the help of a model they are extrapolated for lifetime estimation. Incidentally the accuracy of such measurements even for fixed xenon ion energy and incidence angles is usually uncertain by considerable amount, in spite of the usage of techniques like Cavity Ring Down Spectroscopy (CRDS), quartz crystal microbalance, in-situ profilometry. CRDS uses laser based sensors for monitoring sputtered BN from Hall thrusters which is a non-intrusive diagnostic method [12]. Other measurement techniques have their own advantages and disadvantages [10] OES method has proven to be most reliable in terms of time constraints but still it has been claimed that the fluorescence signal is difficult to relate to absolute boron concentration, as the exact rate of boron excitation is unknown [10]. This paper also deals with same OES method. This work proposes the OES method with imaging which obtains a 2D projection of the characteristic emissions by various species in the plume. We show that these images can be quantitatively analyzed over a broad range of operating parameters and for a very long duration of firing with sufficient self-consistency. Thus, we have a powerful method at hand which predicts a relative erosion rate which can then be compared as function of operating parameters as well as long term qualification testing of the thruster.

The collision among the various species present in the plasma like electron-neutral, electron-ion and electron-electron collisions are important as the collision frequencies are associated with them which decide the plasma behavior. These collisions can result into excitation as well as ionization of the neutrals which depend on the scattering cross-section of the collisions. The effective electron-neutral scattering cross-section for xenon is the function of electron temperature. Mathematically, it can be represented as [1]

$$\sigma_{en}(T_e) = 6.6\times10^{-19}\left[\frac{\frac{(T_{eV})}{4}-0.1}{1+\left(\frac{T_{eV}}{4}\right)^{1.6}}\right][m^2] \tag{1}$$

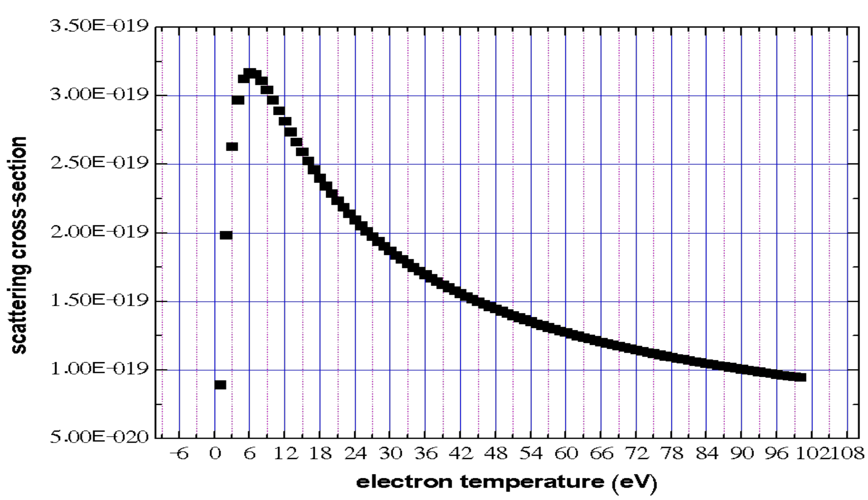



**Figure 1. Scattering cross-section as a function of electron temperature**

The plot reveals that the scattering cross-section is maximal for the electron temperature of 6eV and in general it has been found that the electron temperature inside the plasma is 2-20eV where we can see that, the cross-section is high [1].

In general, the techniques and methodologies adopted for analysis are Mass Spectrometry, Optical Emission Spectrometry [12] etc, however, it is difficult to determine the erosion rate with Mass Spectrometry [11], considering the need of deflection and detection mechanisms required to do the same. Hence, the emphasis was given to the use of Optical Emission Spectrometry which is measuring and analyzing the spectrum of the emitted light from the plasma. Inspection of the erosion dynamics can be done by "Intrusive" and "Non-Intrusive" [12] measurements. The drawback of intrusive measurement technique is the damage of the probe because of the high temperature plasma coming out of thruster. Also, there is exists possibility of plasma poisoning due to the materials used to make the intrusive probes. As the probe used for intrusive measurement comes in contact with the hot plasma, it gets sputtered and thereby causes plasma poisoning.

## II. Methodology

This work enhances the effectiveness of an already established method of Optical Emission Spectroscopy (OES) [7]. In the conventional OES the light emitted by the thruster plasma is analyzed via a high resolution mono-chromator and a photo detector. The probes of this nature usually accumulate information over a large volume hence require sophisticated optics to localize the active volume and are relatively inflexible in obtaining a 2D or 3D profile. However, this can be overcome by using the method of imaging with the help of CCD CMOS camera having multiple optical band pass filters. Each filter corresponds to a specific specie in the plume. Thus the image produced with such filters represents a 2D projection of the distribution of specific species. The images of the plasma plume at the thruster exit have been captured from a distance of approx. one meter. The camera is placed perpendicular to the exit plane of the thruster as shown in Figure 2. The images taken with these cameras are the raw images shown in Figure 3.

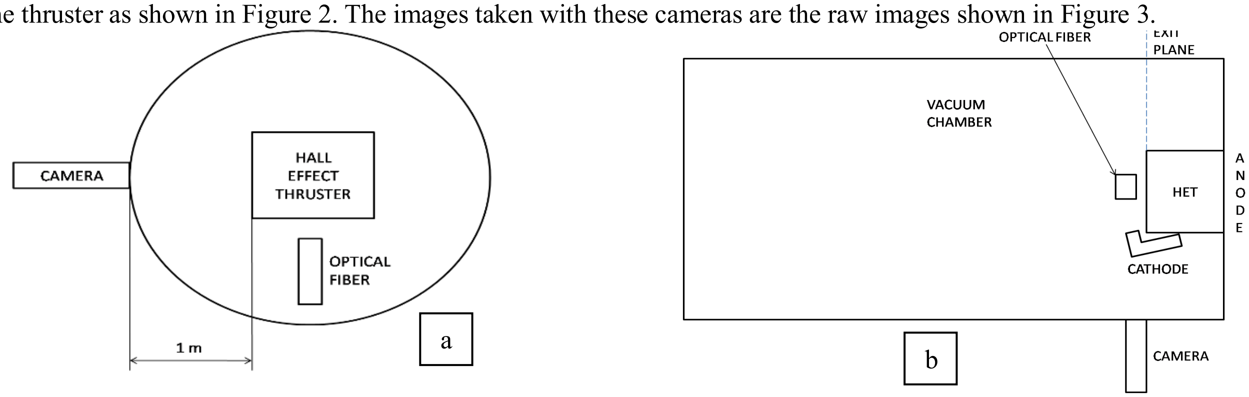



**Figure 2 (a) and (b). Front view and top view of the schematic respectively**

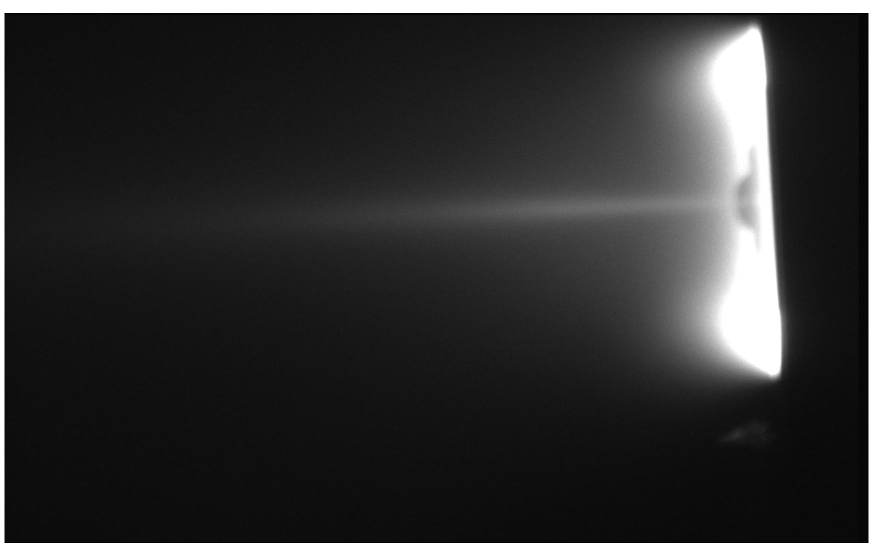


**Figure 3. Raw image taken with camera [3]**

This technique is Non-Intrusive and real time with the camera placed outside the testing vacuum chamber. The analysis and the diagnosis of the images was carried out in "Origin Lab" by determining the area under intensity curve of the images at proper positions to understand the plasma behavior. It is essential to choose proper position to understand the plasma behavior as the intensity in the channel is higher where the cathode is closest to the channel. Also, electric field based on its magnitude imparts different velocities to the ions making some ions to travel faster and to longer distances than the others. Hence, its these high velocity ions which forms the jet of the plume and thereby produce thrust. This gives us a conclusion that the xenon ions which face more electric field will travel longer distance and is the sole contributor to the thrust generation as compared to the impurity elements coming from the Ceramic material.

The jet formed is because the xenon ions move with high velocity and emit light while travelling. These fast moving xenon ions travel for longer distances and during the process ions undergo recombination with electron and emit light. However, the elements produced from the ceramic have lower velocity so these particles emit all of their light over a short distance. The Xenon ions emit the light in two ways, while recombination and while de-excitation. It is the de-excitation process which forms the plume. These de-excitations take place from the metastable states which hold the system in excited state for a longer duration because of which ions emit light relatively over longer distance. So, in the case of Xenon ions and neutrals, the position chosen to understand the plasma behavior is relatively far from the exit so that an actual estimate of the plasma behavior can be made. While, in case of constituents of the ceramic liner investigation has to be done near the exit as ceramic particles do not travel longer distance. Hence, this technique determines the temporal as well as spatial dynamics of the plasma plume. The camera has 8 filters of certain wavelength bands as given in Table 1.

| Wavelength (nm) | Wavelength Band (nm) | Dominant Species |
|---|---|---|
| 254 | 20 | Ceramic |
| 290 | 21 | Ceramic |
| 410 | 5 | Ceramic |
| 475 | 50 | Xe-II |
| 509 | 20 | Ceramic, Xe-II |
| 515 | 10 | Ceramic, Xe-II |
| 717 | 10 | Ceramic, Xe-II |
| 750 | 10 | Ceramic |

**Table 1. Dominant species in the different wavelength bands**

Our main focus is on Si, B, O, N and Xe neutrals and ions (singly ionized) as it has been seen that highly ionized species are relatively less in number density.

The absence of plume in the 254nm and 290nm filter images is inevitable as these filters map the species such as B and Si from ceramic liner which do not travel far distance and spread out soon (Because of the effect of electric field profile in the thruster channel, these species do not get accelerated to higher potential as compared to the Xenon ions. This is because the ceramic erosion takes place maximum at the exit where the electric field strength is relatively low, hence the ions get less energy). To inspect a particular element, other wavelengths need to be filtered out. This is achieved using a camera with filters which allows a particular wavelength band of light to pass through it. The choice of selecting particular band of wavelength is also a concern because of the constraint on the cost of very narrow band filter which can select a particular element only. Each filter analyzes the dominant species listed above in Table 1 which were determined from the NIST database [2]. By finding the area for a particular channel we can simply estimate the number of particles present as the ions undergo recombination process with the electrons supplied by the cathode while coming out of the thruster exit.

With the help of NIST data, it was found out that for a particular filter there exist multiple characteristic wavelengths. Since it is known that different atoms have the different energy gap, so the transitions between these different accessible energy levels give rise to different wavelengths. But, wavelengths emitted by different species in the actual plasma conditions are entirely different as compared to those mentioned in NIST database. NIST database provides an approximate idea about the species dominance in different filter wavelength band. These wavelength bands are band pass filters which practically can be assumed to have Gaussian shape. To get proper intensity for each filter, Gaussian function for every filter is imposed on the NIST data.

The NIST intensity data is then over plotted with the OES (optical emission spectroscopy) data to estimate the relative population of different species. This way, the availability of various dominating species for different filters was crosschecked. Figure 4 and Figure 5 show the same.

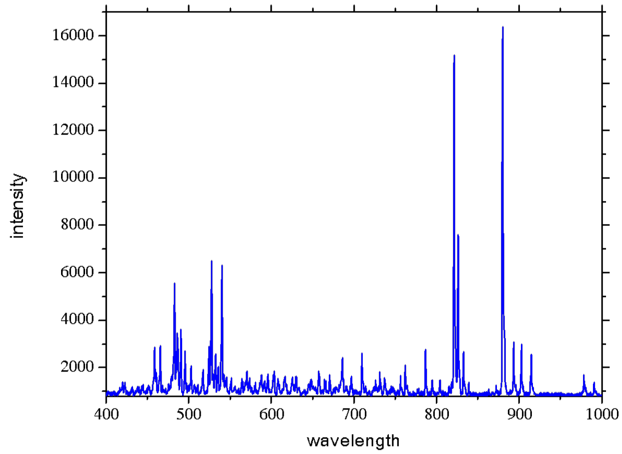



**Figure 4. Column plot for complete NIST data in the vis-IR range from 400nm to 1000nm**

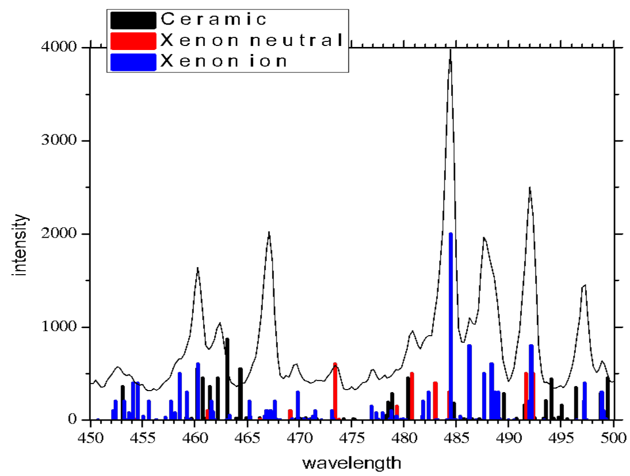



**Figure 5. Comparison between NIST data and OES data for 475nm wavelength filter**

In the wavelength range from 245nm-255nm under certain operating conditions, according to Pagnon [3,4,5], the intensity of B and Si neutrals increase by a factor of 4 while that of Xenon ion remains almost constant. At the same time, as per Celik [6] the total integrated intensity of B neutral exceeds that of Xe+ at high discharge voltage. However, as per our work, considering the 244nm-264nm wavelength range, there are several lines from the constituents of ceramic (B, Si, N, O) and after integrating intensity the effect is more pronounced. Hereby, knowing the fact that the intensity of Xe+ remains almost constant, ratio of intensities of 254nm and 475nm gives a clear picture about the variation of intensity of ceramic with respect to Xenon ions (discussed later in Observations and Results section). These techniques lead us to the conclusion that 254nm and 475nm filters correspond to the Ceramic and Xenon ions respectively.

As the thruster starts, the plasma plume is in diffused state and then the plasma plume switches to the jet mode within 100 s of start. After attaining the jet mode, plume intensity variation is very smooth and it does not undergo huge fluctuations. While initially there are rapid changes in intensity which are discussed in detail in “Observations and Results section”.

The 350W thruster was tested for long hours during which the images were taken. The intensity as a function of time has been plotted for different filters separately at different channels (positions) away from the thruster exit. These channel numbers are also the row and column numbers. This can actually be realized using the “profile” which shows the projection in terms of intensity. Figure 7 shows an example of one such profiles.

Side view of the thruster gives a sense of two exits from the thruster and there is difference in intensity between the two exits as can be seen in the Figure 6. These plots are merged together to see the intensity difference. This difference is because cathode is near to one of the exit and hence the intensity is different at two locations.

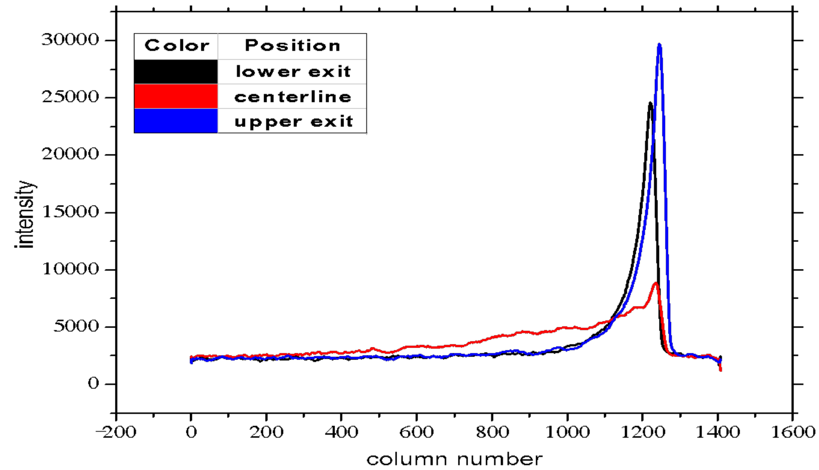



**Figure 6. Difference in intensity at the lower and upper exit**

So, the analysis has been done for the one-half of the image which does not include the exit near to the cathode to get more accurate intensity of the species of interest.

## III. Results and Discussion

After the analysis, differences between behavior of Xenon and Ceramic constituents in plasma were observed. This can be demonstrated using the profile for both cases. In plasma plume, the presence of Xenon neutrals and ions is found even at several meters away from the thruster exit, whereas the presence of Silicon (Si) and Boron (B) dies off within few centimeters away from the exit of the thruster. Figure. 7 and Figure 8 shows the plume profile for 254nm and 475nm wavelength filters.

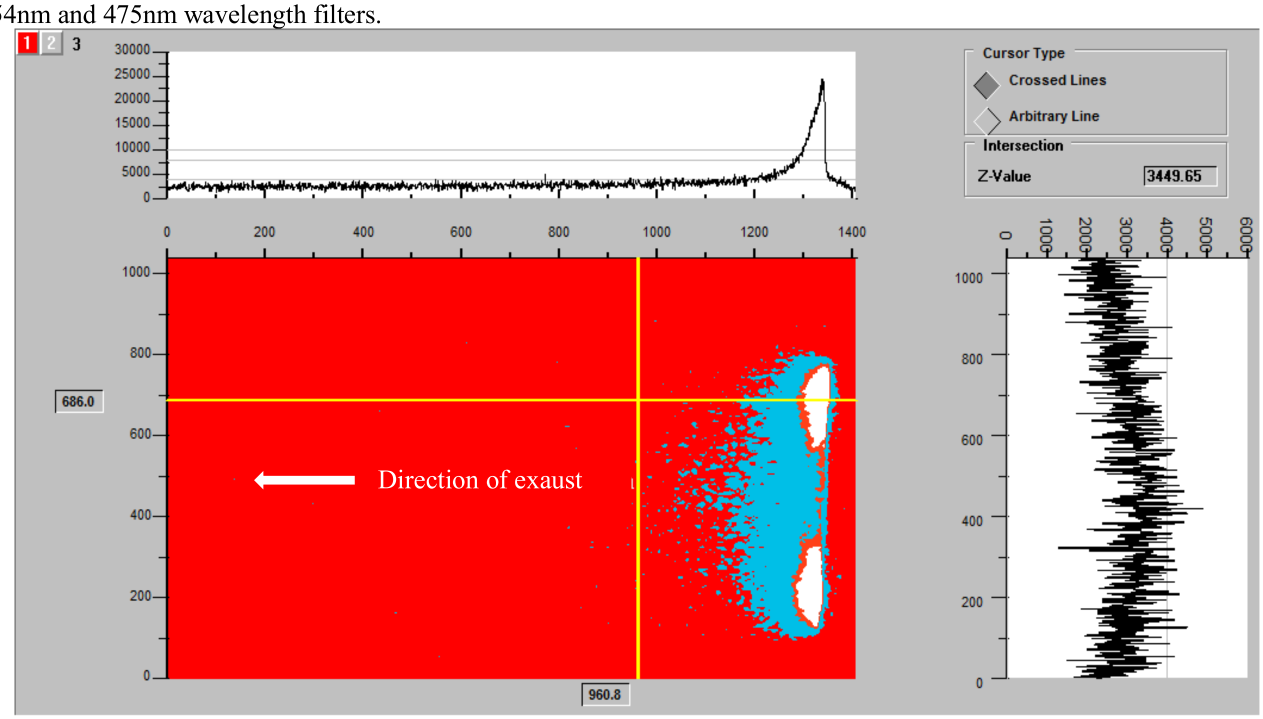



**Figure 7. Plume profile for 254nm wavelength filter**

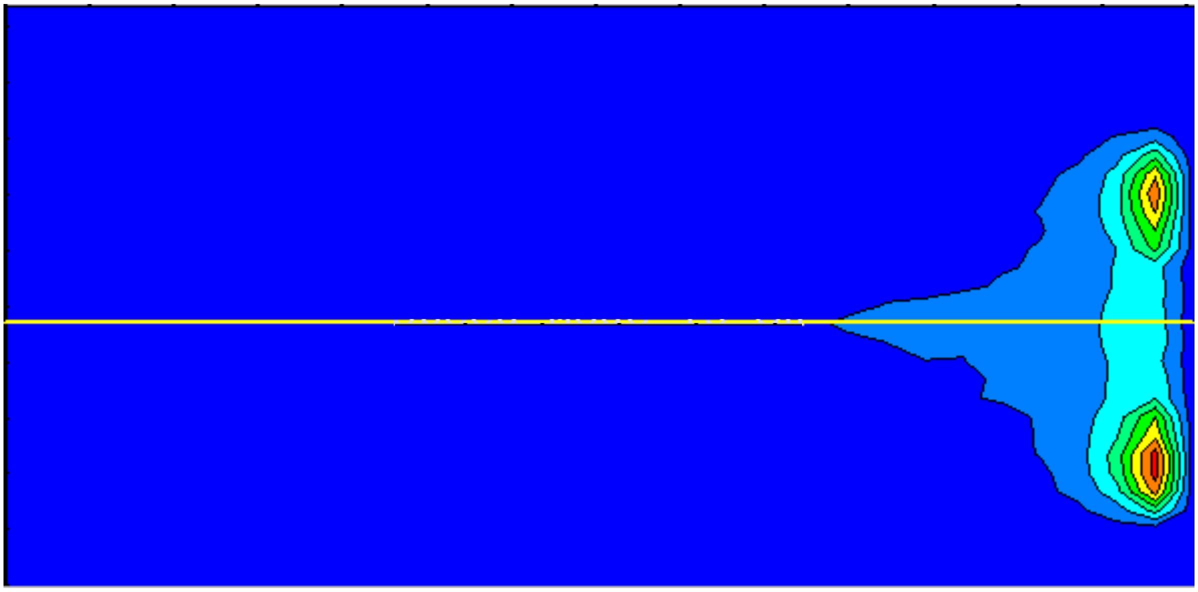


**Figure 8. Plume formation for 475nm wavelength filter**

Figures above clearly show that the plume is long in case of Xe+ (475nm) compared to Ceramic elements (254nm).

It can be observed from the plume region that the intensity of the plume decreases near the exit and then increases outwards. This is because of the Magnetic field profile which persists due to the structure of these thrusters. The outer magnetic pole acts as the North Pole and inner magnetic pole acts as South pole, because of this arrangement the magnetic field lines and flux is high in the thruster centerline region. This is the reason why the Plume is visible in front of the Centerline and not at the outer diameter of the channel. Electrons trapped by magnetic field move in a spiral motion around the flux lines but, as the electrons come closer to the South Pole they do not reach the thruster centerline rather they change their direction of motion back towards the North Pole possessing an oscillatory motion. So, the gap region where these electrons do not go is the region in which we can see the intensity to be less. Figure 9 shows the Plume intensity variation with respect to the distance from the Thruster Centerline.

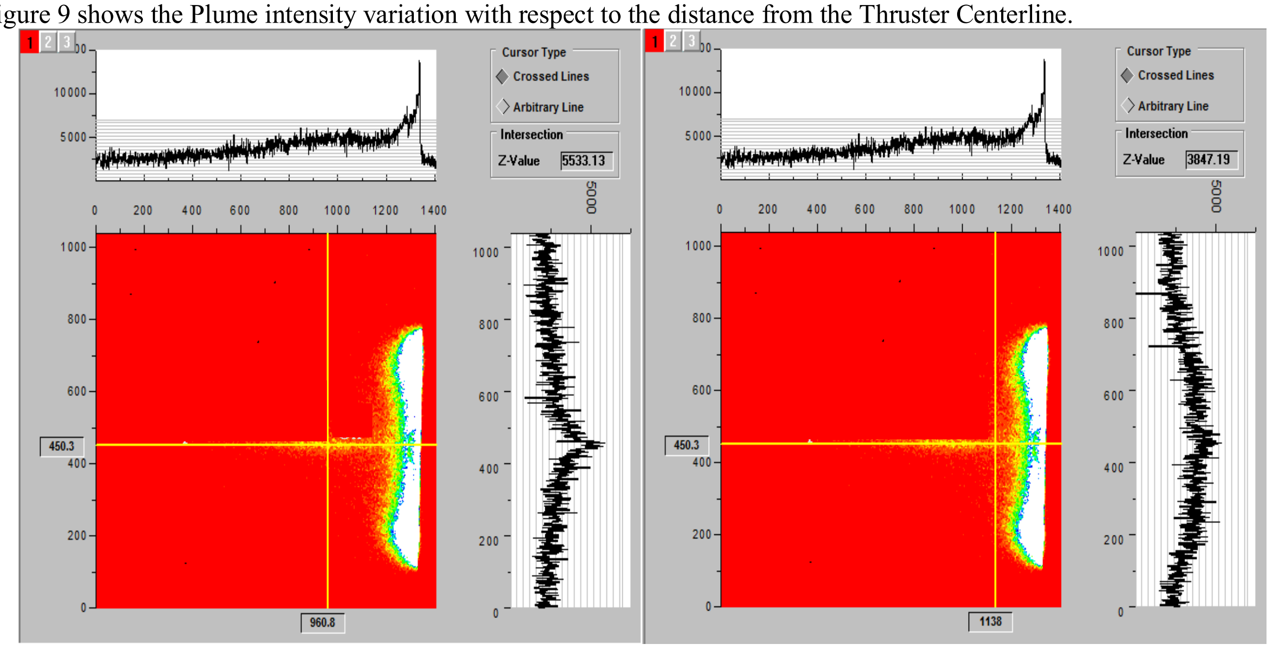
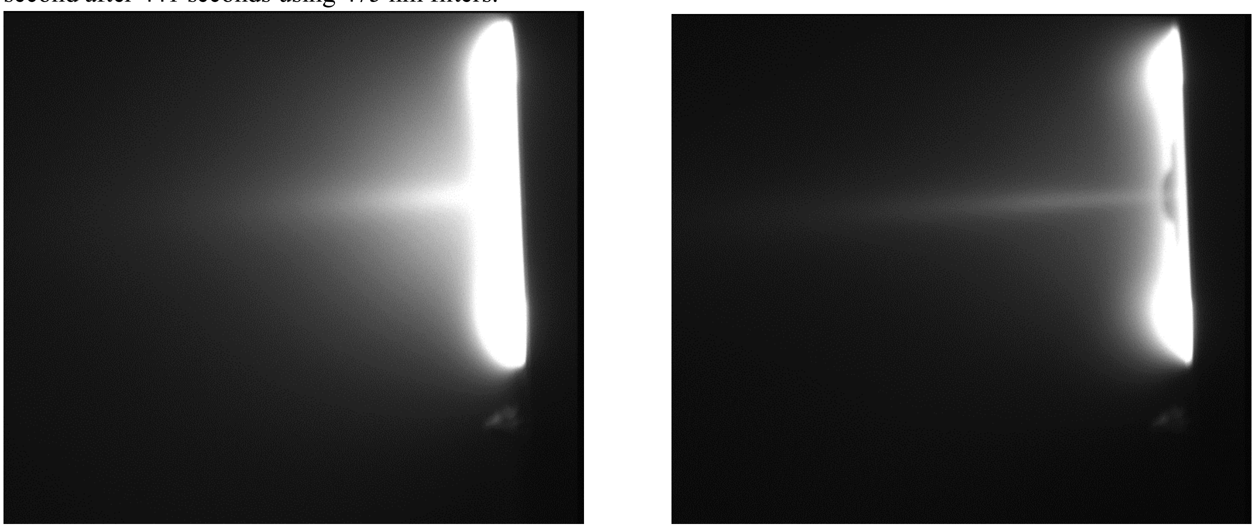



**Figure 9. Intensity variation with respect to the distance from the thruster center line**

In order to determine the rate of erosion, a study of the temporal dynamics of the plasma intensity was carried out. The number density of ceramic species and its variation decides the amount of ceramic material eroded with time. This unique diagnosis has helped out in determining the rate at which the erosion is taking place and can be analytically related to the prediction of amount of erosion in ceramic with respect to time. Hence, this methodology can help in deciding the lifetime of the thruster as the duration for which the ceramic liner last will be known beforehand. With the other techniques it takes longer time to find out the lifetime of the thruster as the more number of tests are required to predict the erosion. This is expensive and requires work force as well. Also, the other techniques have their demerits in form of complexity of the method and fidelity of the result. So, with the advent of this new method it will be pragmatic to overcome this existing problem in the field of electric propulsion.

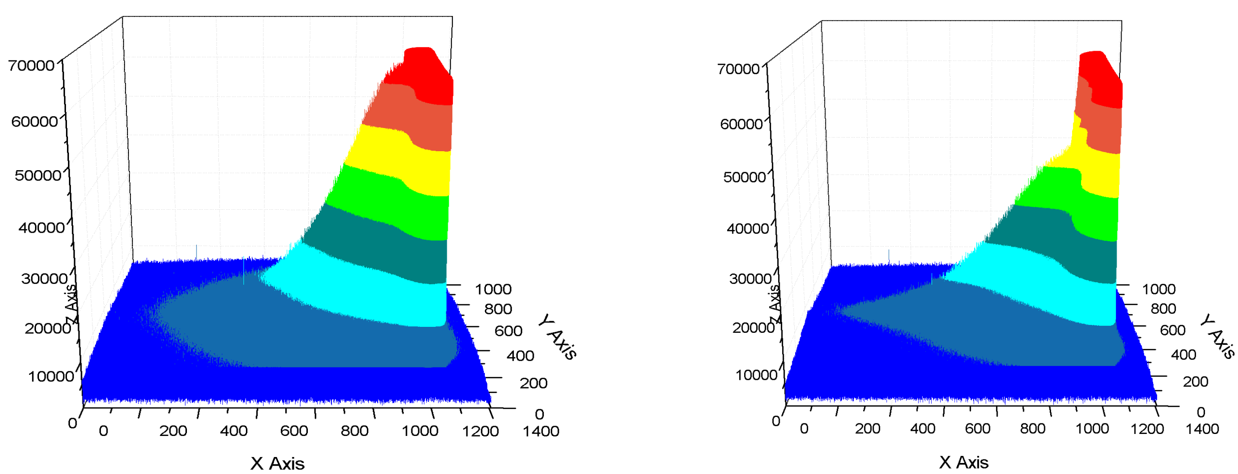
It is observed that the erosion of the ceramic liner is visible as the intensity of the ceramic components is initially high and decreases rapidly with time because of two main reasons: the polishing of the ceramic surface takes place at the start of run, in which the dust and other particles which gets attached to the surface of the ceramic when the thruster is kept in ambient conditions. This initial polishing during the start of the thruster gives a higher intensity, mainly due to surface contaminants degassing out of the ceramic liner and disturbing the plasma conditions. The actual estimation of the erosion process during this phase has never been estimated in past. The method proposed in this work helps in doing such measurements. Figure 10 shows a pair of images taken close to the first few seconds after firing and the second after 441 seconds using 475 nm filters.



(a) (b)

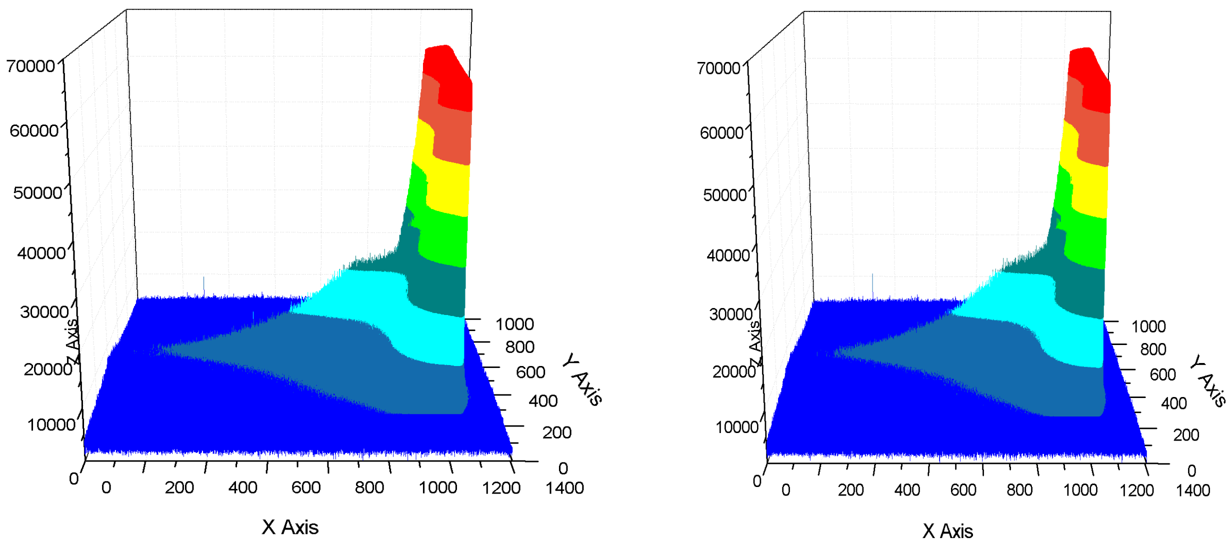
**Figure 10 (a) and (b). Raw images [3] taken close to first few seconds after firing and after 441 seconds respectively.**

The intensity is plotted in a 3D graph in Figure 11 and Figure 12 to elucidate the point




(a) (b)

**Figure 11. 3D color plot for image just after thruster start**




(a) (b)

**Figure 12. 3D color plot for image after 440 seconds of firing**

The thruster was operated for several runs and the camera was placed outside the vacuum chamber, so due to the change in the placement of the camera, the field of view of the camera changes. Due to this the intensity fluctuates with different runs, hence we plot the comparison between 254nm and 475nm run-wise. Also, the normalization varies run-wise and it's easier to do the normalization and comparison.

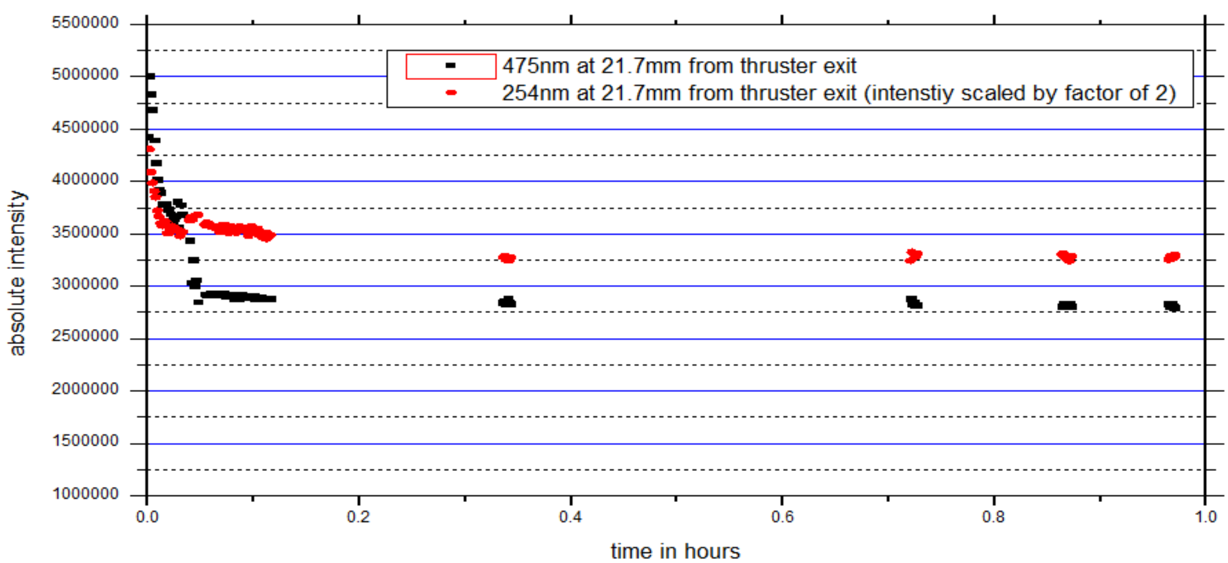



**Figure 13. Absolute intensity plot w.r.t. time for 254nm and 475nm on run1 (scaling is done for comparison)**

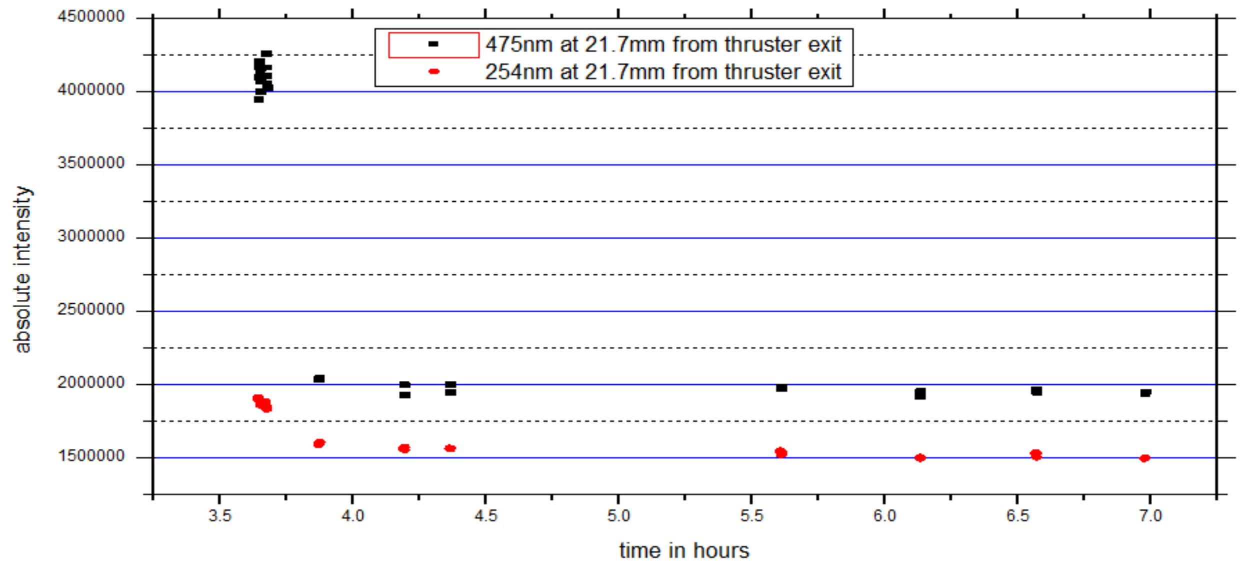



**Figure 14. Absolute intensity plot w.r.t. time for 254nm and 475nm on Run No. 2**

The Figure 13 depicts that after entering jet mode (at time 0.04722 hours i.e. 170 seconds) the intensity of $Xe^+$ becomes almost constant while ceramic intensity decreases gradually. This gives a hint that one can normalize the ceramic intensity plot with Xenon ion intensity which has been plotted in Figure 15.

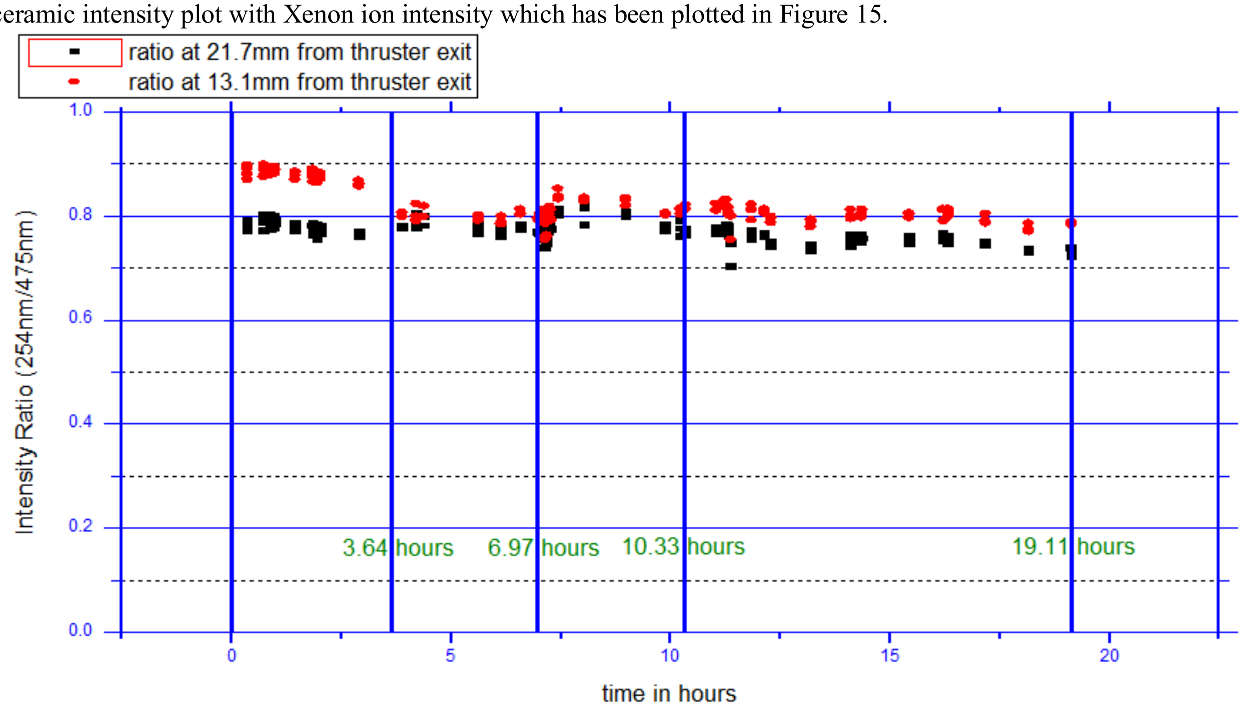



**Figure 15. Cumulative plot of (254nm/475nm) ratio for the complete 4 runs of 19.11 hours**

It was observed that gradual reduction over time took place in the erosion rate which is a well-known phenomenon. This occurs due to the fact that as the ceramic erosion occurs, the ceramic liner gets shaped to an optimum profile leading to systematic reduction in the erosion. The variation of the erosion rate is very smooth and observed to be decreasing slowly. These observations are in agreement with the expected behavior as per the existing literature.

## IV. Conclusion

A unique and novel method to perform non-intrusive real time analysis of erosion process in the HET was developed, demonstrated and validated. This process is of immense significance for the practical usage of a thruster as well as developing the most suitable operating envelope. The analysis of the two dimensional intensity profile provide vital information regarding plume divergence, Xe ion and Xe neutral distribution, ceramic erosion and related operating conditions. With this method it has become possible to test the operating quality of the thruster, which was extremely difficult, time consuming and manpower intensive job, in real time by changing operating parameters. Moreover, a relative erosion rate estimate on long term erosion and lifetime estimate can also be achieved by this method.

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