Measurement of Plasma Parameters using Digital Image Processing Technique

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ABSTRACT
Digital Image Processing Technique (DIPT) is a widely used technique for image processing activities in digital communication. Its use as diagnostic tool is in recent use in many experimental researches, where emission spectroscopy plays a dominant role. In this work, we have projected DIPT as a low cost and non invasive probing technique to measure different physical parameters like energy, temperature and density of a DC Glow Discharge Plasma. The radiative emission from DC Glow Discharge Plasma is normally in the visible range along with some infrared and ultraviolet emissions. The frequency of such radiations indicates the energy of the radiation. Different radiative processes in the plasma are responsible for the frequency band of the emission. The spectral distribution depends upon the homogeneity of the plasma also. By analyzing the image of plasma we can infer the spectral distribution due to emission from different regions of the plasma. Here, we have evaluated the matrix of rgb values of pixels of the plasma image. We have developed an approximate relation of the rgb to the wavelength of the spectra. The corresponding frequency matrix is then worked out from the derived wavelength matrix. Then considering a local thermodynamic equilibrium, the energy distribution matrix, which depends upon the local atomic processes, is calculated using the above frequency matrix. The surface plot of the temperature, density and the energy of the plasma have been shown in this work.

General Terms
Digital Image Processing, Plasma diagnostic, Imaging Plasma Technique, Glow Discharge Plasma, Plasma parameters.

Keywords
Digital Image Processing, Plasma Probing Technique, Glow Discharge Plasma, Plasma parameters, State of Ionization of plasma.

1. INTRODUCTION
Digital Image Processing is a widely used technique in variety of fields like communication engineering, bio medical applications, computer image processing, space physics to nanotechnology. The basic of this technique lies in the analysis of a digital picture of any phenomenon and to reveal the actual facts of the processes about the phenomenon [1]. In particular if the picture is taken to understand any physical processes under consideration then the analysis part requires the knowledge of the physics responsible for the processes. The underlying basic principle in all digital images processing technique is to extract the information from the color of the pixels. Different methods like r,g,b or c,i,e schemes, gray scale representation or some alternative color schemes are used to decipher the color values of the pixels [2]. The color sensitivity of the instruments is another important factor that affects these values for evaluating, as the actual values corresponding to the actual phenomenon may be different. There are number of image processing algorithms developed for processing of the image data for different experimental observations [3-6]. Refinement of the images is highly essential to remove distortions and noises in the images and for processing of images to minimize errors arising due to instrumental limitations.

In the beginning, this technique happened to be priced possession of the computer scientist for image compression for various communication and information purposes. Of late, image processing technique [IPT] has proved to be an inexpensive and advantageous diagnostic method for many physical phenomena where there is an emission of radiations. Moreover, in the situations where direct measurement of structural changes is limited by its size, imaging technique is proven to be a powerful probing method to know the structural morphology or may be the surface topology in case of surface coatings.

The extensive use of this technique in pattern recognition [7] has helped in understanding many in depth phenomena without much difficulty. Pattern recognition has been used for various scientific analyses in bio-medical areas and digital communications. DIPT is a very extensively used to investigate the physics of different space and astrophysical phenomena. The observation of white light solar flare is reported by imaging technique analysis by Heliosesmic Magnetic Imager at the Solar Dynamics Observatory [8]. The DIPT has been used in a comprehensive manner to give a systematic overview for feature-detection from solar data for visualization of solar imagery, cataloguing, statistics, theoretical modeling, prediction, and forecasting [9].

The use of DIPT for the surface characterization at a nanoscale is very extensive. Image processing has been used as a non-invasive technique for inspection and characterization of nanomaterials and structures [10]. The study of fractal aggregates composed of nanoparticles [3] and characterization of material surfaces morphology, grain size, roughness and shape analysis during surface coatings by deposition of nanoparticles has shown very good results with the help of IPT [11 - 13].

With the fast development of image capturing technology over the last decade, the use of DIPT is also extending to cover newer and newer areas of science. The development of sophisticated cameras with higher resolutions, minimum aberrations, color sensitivity and wide ranging light capturing capability from infrared to ultraviolet wavelengths has brought about a revolution in this field.

The use of IPT in plasma physics is mainly used for analysis of surface engineering by plasma deposition [14]. Its use for characterization of plasma is not yet exploited to its full potential. The discharge processes in glow discharge plasma emits radiation. The process of gas discharge is a complicated phenomenon [15], which is of high interest for the plasma physicists. The spatial distribution of the energy in the plasma was analyzed using the images captured by a CCD (charge coupled device) of atomic emissions in argon plasma [16]. Monochromatic imaging is used as a plasma diagnostics for the two-dimensional monochromatic images in the visible region of an aluminum cathodic arc burning in helium background gas [17].

In case of dusty plasma consisting of submicron particles suspended in an argon RF glow discharge, the electron temperature is evaluated from the intensity ratio of two atomic or ionic spectral lines from the information derived from the pixels of the image [18]. In another work as reported in Ref. [19], it shows the successful use of imaging technology to demonstrate the demixing of the argon and helium in argon-helium arc plasma. Helium is shown to concentrate in the high temperature region near the center of the arc, and the radiative emission from helium, relative to that from argon, increases with temperature. Plasma-imaging has been used as an effective probing technique on the HL-2A tokamak, to understand the basic plasma discharge scenario of the entire torus and to check the plasma position and the clearance between the plasma and the first wall during discharge [20].

In a review article [6], the authors gave an elaborate description of the development of high-resolution plasma imaging and spectroscopy diagnostics for the soft X-ray and ultraviolet energy ranges. The future of such diagnostic will be very high on larger scale facilities throughout the world. The measurement of velocities of plasma flow or rapid processes in plasmas has always been very difficult. IPT has proven to be very successful in this direction [21-24].

The measurement of density distribution of plasma has always been a critical issue. A very successful presentation of the density distribution has been shown by using a coherence imaging technology [25]. The concurrent physics of Stark broadening of the H_γ line was used to find the local density values by the Abel inversion of the measured interferometric fringe contrast. The IPT has come out to be a very useful optical technique for determination of tokamak plasma column displacement by using the emission intensity profile [26].
In this contribution we have presented DIPT as a non invasive and inexpensive probing technique to determine the different plasma parameters like temperature, density profile and energy distribution near the electrode in a dc glow discharge plasma. With the help of this technique we will try to throw some light on the process of discharge in plasma produced by a dc electrode discharge.

2. THE EXPERIMENTAL SYSTEM

2.1 Description of the Experimental Setup

A cylindrical stainless steel vessel of 37 cm long and 21 cm inner diameter as shown in figure 1 is used to produce the plasma. The vessel was evacuated to a base pressure of 10^{-4} mbar using a rotary pump. Then air was inserted in a controlled manner and a constant working pressure of 0.2 mbar was maintained.

Figure 1. The experimental setup for plasma production

Discharge was created between two circular steel plates of 5 cm diameter each and at a separation of 10 cm between them. The plates were not coated on the opposites by any kind of non conducting coating materials to see the plasma on both sides of the plates. The plates were kept along the axial direction of the cylinder. A variable dc power supply of 1 KV and 1 A was used as the source for producing the discharge. Discharge current was measured using a milliammeter (1 mA – 25 mA). A resistance in series with the milliammeter was used as a safety measure.

A digital Nikon camera of 10.3 mega pixel was used to capture the images of the plasma under different conditions. The camera was placed near to the view port facing the electrode directly. A distance of 8.0 cm approximately was maintained from the plates to the camera. Pictures were taken in the macro mode to get a close up view. Dark room conditions were maintained to avoid scattered light from other sources.

2.2 Operational Procedure of the Experiment

The initial discharge current was observed at a discharge voltage of 350±5 V. The current was slowly increased by increasing the discharge voltage and ultimately an almost stable discharge current of 10 ± 0.5 mA was maintained. The discharge voltage observed was 750±5 V.

As the discharge voltage was increased the intensity of the color of the plasma also increased. The emissive radiations from the plasma were significantly high since the plasma was highly collisional. Fig. 2 shows the image of the plasma confined near the cathode plate at this voltage. Pink violet color plasma was observed with marked spectral distribution from whitish-pink to deep purple toward the periphery of the vessel. Images at different discharge current were also taken. Noticeable difference was observed in the intensity and color also.

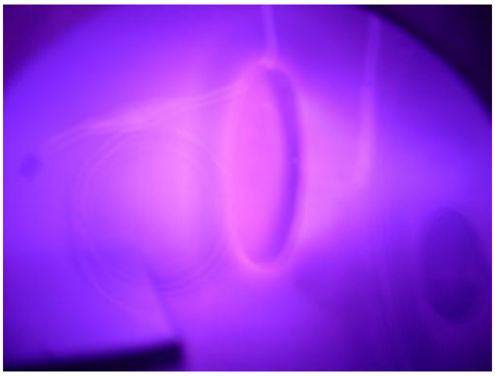

Figure 2. Image of the glow discharge plasma near the cathode

3. QUANTITAVE ANALYSIS METHOD

3.1 Analysis using IPT

We adopted the rgb color scheme to determine the pixel values of the image. The digital picture was zoomed up as shown in figure 3 to show the pixels whose rgb values are to be determined. The matrix of the rgb values are found using image processing tool of Matlab 7.0.

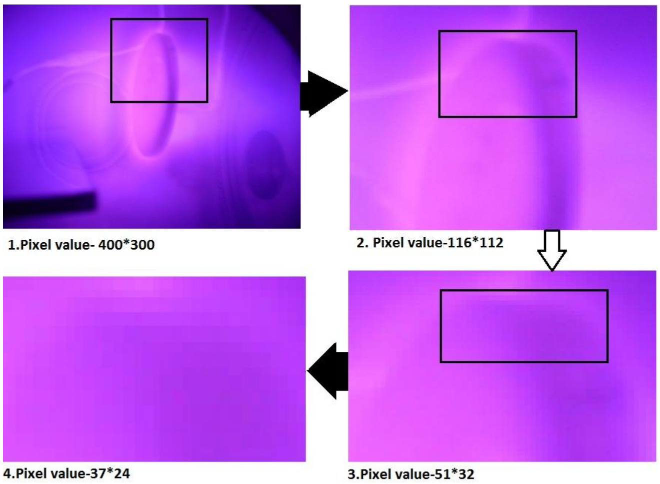

Figure 3. Zoomed up of the image to find the pixel values

The emission from the plasma is an indirect measurement of few of the important atomic processes undergoing in the plasma. The color of the plasma depends upon frequency of the light emitted during the atomic and ionic excitation of the plasma species.

There is no direct connection of the rgb values with the wavelength of light. The rgb values are affected by different parameters like hue, saturation or beta values of color. The prime objective of our problem at hand was to find a relation to evaluate the wavelength (λ) for any given value of rgb. There are some schemes to find the rgb values for a given wavelength [27].

A database of the rgb matrix for a continuous variation of the wavelength was developed. Using this database plots for the variation of r-value, b-value and g-value w.r.t. λ are drawn. The plots are shown in figure 4. As, the plots are not direct consequence of some physical principles, a definite relation was not in hand. Moreover, the plots are three different graphs without any common resemblance in their nature; it is difficult to build an equation for the evaluation of wavelength for any given value of r, g and b, i.e. $\lambda \equiv \lambda(r,g,b)$. Even though exponential fit comes close to represent the r and b value with λ but it will lead to a high error for the evaluation of the wavelength, as g do not fit into such types of exponential fits.

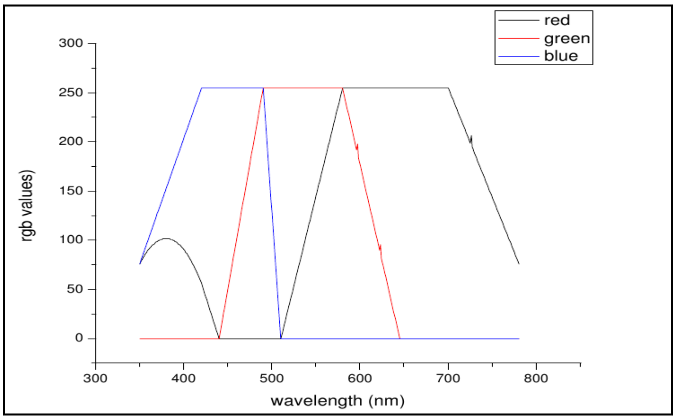

Figure 4. Variation of the r,g,b values w.r.t. wavelength

At this juncture we have adopted a scheme to break the complete spectral range into number of small ranges. For each of these ranges separate polynomial fits with a maximum of third order are used to fit the plotted data. Hence, we derived three separate equations of the wavelength in terms of r, g and b values uniquely. These three wavelength functions are combined using different weight factors α, β and γ for r, g and b valued λ respectively. Thus, a complete equation of $\lambda = f(r,g,b)$ is derived.

The equations depicting the wavelength as a function of the r, g, b values in the different wavelength ranges are shown in table 1 and the corresponding values of the weight factors are given in table 2. Still, we had a problem as the functional form of $\lambda = f(r,g,b)$ is different in the different ranges of the wavelength. In our work we made a filter arrangement to check for the r,g,b values where the same r-value, g-value or b-value corresponds to different wavelengths. Of course, none of the two have the same value simultaneously. The corresponding wave equations pertaining to the same pixel value regions are used to check whether the evaluated wavelength lies in the visible range of the optical spectrum in first place. The other parameter in ascertaining the proper equation was decided by considering the gradual variation pattern of the wavelength in purview of its preceding and succeeding value of the wavelengths. This is justified by the reason that the emissions in the plasma will follow a gradual variation behavior only due to thermodynamic equilibrium.

3.2 Physical Models for Quantitative Analysis

The DIPT adopted was elaborate and satisfactory to minimize the error in calculating the closest wavelength for a given set of r,g,b values of a pixel. Using this methodology a wavelength matrix was calculated for the image in figure 2. The basic relation of $E = hc/\lambda$, where E is the energy, h is the Planck's constant and λ the wavelength is used to generate an energy distribution

Table 1 The Equations of the wavelength in terms of rgb values

λ (nm)	FITTED EQUATION FOR THE RANGE
350-383	$\alpha(-1616.72+68.35204r-0.79506r^2+0.00311r^3)+\beta*0+\gamma(320.06864+0.39153b^2)$
384-420	$\alpha(615.49793-7.5928r+0.0997r^2-0.0004656r^3)+\beta*0+\gamma(320.01994+0.39215b^2)$
421-440	$\alpha(440.022-0.35324r)+\beta*0+\gamma*255$
441-490	$\alpha*0+\beta(440.00792+0.196g)+\gamma*255$
491-510	$\alpha*0+\beta*255+\gamma(510.0043-0.0745b)$
511-580	$\alpha(509.99168+0.27456r)+\beta*255+\gamma*0$
581-645	$\alpha*255+\beta*0+\gamma(645.052-0.2547b)$
646-699	$\alpha*255+\beta*0+\gamma*0$
700-780	$\alpha(814.19163-0.4472r)+\beta*0+\gamma*0$

matrix for the corresponding wavelengths of the pixels. The energies corresponding to the pixels correspond to the energy of the plasma at different physical positions inside the chamber. The energy is an indirect measurement of the temperature distribution of the plasma. Moreover, the density of the plasma also depends upon the energy distribution. The temperature was evaluated by considering a blackbody radiation given by the following equation,

$$E=\varepsilon\sigma A\left(T^4-T_0^4\right) \qquad (1)$$

where, ε is the emissivity, σ is the Stefan-Boltzmann constant, A is the surface area, T is the temperature of the radiation and T_0 is the background temperature. Here we have considered the room temperature of 300° K as the background temperature. The plasma is assumed to have a local thermodynamic equilibrium (LTE) [28]. Under LTE the density can be assumed to follow the Maxwell-Boltzmann distribution. The density as a function of the energy at a position is given by the following Maxwell-Boltzmann relation,

$$n=n_0\exp\left(-\Delta E/_{kT}\right). \qquad (2)$$

Table 2 Values of the coefficient of the equations

λ (nm)	α	β	γ
350-383	-0.08	-0.000673	1.0824
384-420	4.424	-0.00132	-3.423
421-440	1.0110	0.00810	-0.01927
441-490	0.000039 2	1	-0.0000392
491-510	0.003526	-0.007189	1.00366
511-580	0.998	0.00403	-0.00203
581-645	0.014	0.9940	-0.00818
646-699	1	0	0
700-780	1	0	0

4. RESULTS AND DISCUSSION

Since air was used as the gas for discharge, therefore mixed plasma was created with nitrogen as the major component. The shape of the plasma was not symmetrical on either side of the plates. A visibly thin dark region on the front side of the plate was observed.

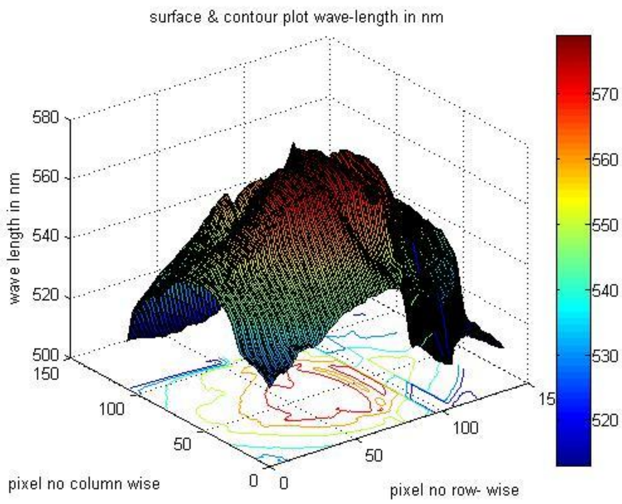

Figure 5. The spectral distribution in terms of wavelength

The color variation was indicative enough to predict the distribution of the energetic species. The variation in the color may be attributed to the demixing of the different plasma

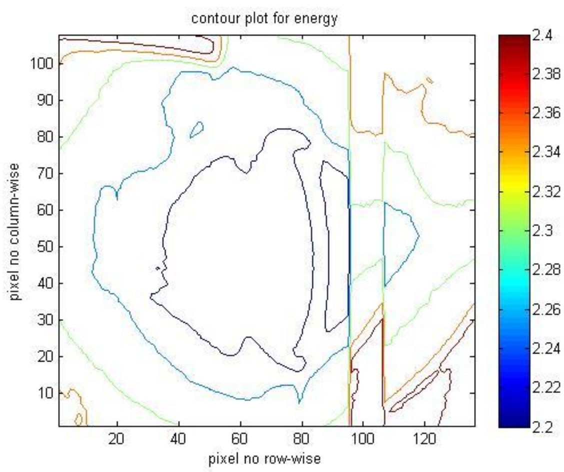

Figure 6. The contour plot of the energy vairation

components at different temperatures. In figure 5 the spectral distribution in the optical range in terms of the wavelength is plotted for the image of the plasma. The variation of the wavelength is observed to be in the range of 500-580 nm. The contours show that longer wavelength is present toward the periphery of the chamber.

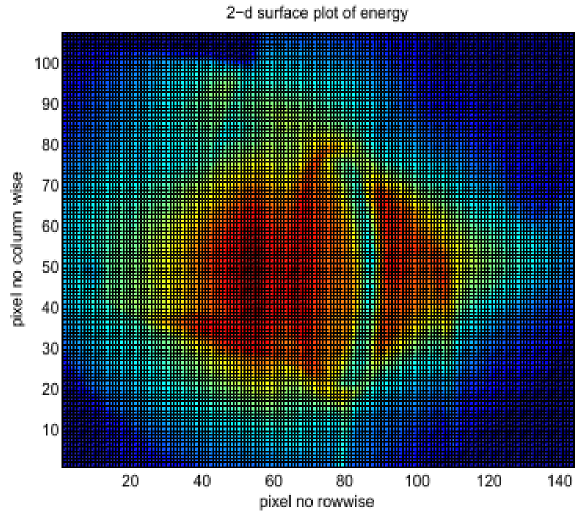

Figure 7. The 2-dim surface plot of the energy vairation

In figure 6 and 7 the contour and two dimensional plots of the variation of the energy are shown. It is seen that the higher energetic particles are mostly toward the periphery of the chamber. It can be conjectured that since the plasma is not confined the plasma is continuously diffusing toward the boundary wall. The high energetic particles will diffuse faster so the energetic particles will be more near the boundary. At the same time since the plasma is multispecies plasma the demixing of the different components also adds to the diffusion. The surface plot shows that the digital image and the reconstructed image using the energy values of the pixel bears close resemblance.

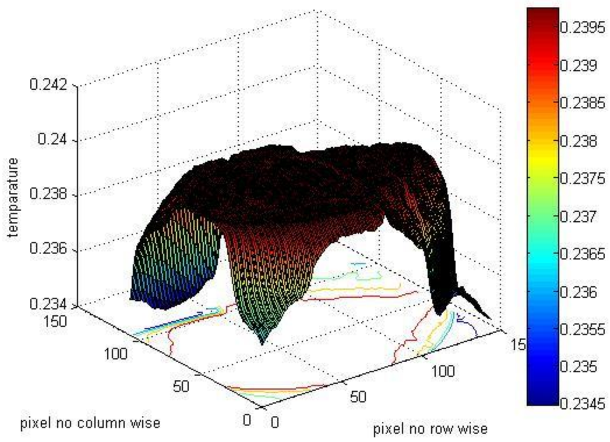

Figure 8. The surface and contour plot of the temporal vairation

In figure 8 the temporal distribution is shown. The temperature varies in the range of 0.234-0.239 eV. The normalized density distribution is plotted using eqn. (2). Figure 9 and 10 depicts the density variation of the plasma as we move from the central

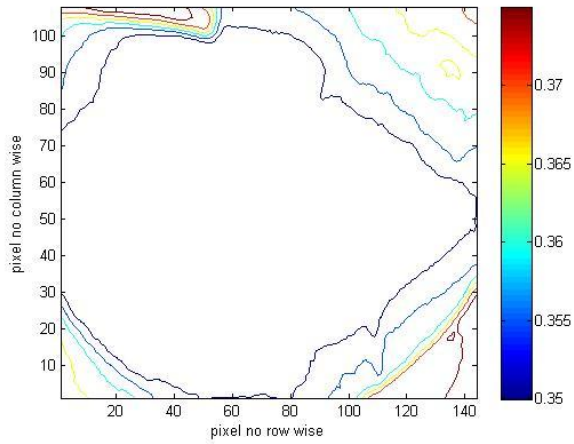

Figure 9. The density variation contour from the central region toward the boundary

region to the boundary of the system. In figure 9 we have considerd the variation with respect to the average temperature of the plasma measured from the energy profile diagram. Whereas, in figure 10 it is plotted by considerin g the minimum temperature value.

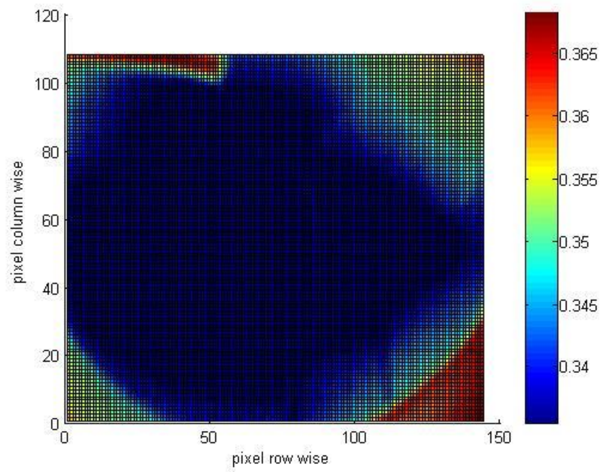

Figure 10. 2-dim surface plot of the density variation w.r.t. the minimum temperature value

A comparison of the spectral wavelength has been made by a standard diffraction grating spectrometer. A plane transmission grating element of 15000 lines/inch was used for the purpose. We have observed the presence of spectral lines of wavelength 415.67 nm, 455.887 nm, 491.22 nm, 511.58 nm, 535.18 nm, 573.55 nm and 617.98 nm in the emission in front of the plate. There are few more intermediate lines of very low intensity also. Since, the spectrometer has its limitation in focusing to very specific regions of the chamber, so the spectral distribution from different regions of plasma cannot be measured.

The advantage of DIPT was that it gave us the spectral distribution throughout the bulk plasma. Further, we would like mention that air has been used as a discharge medium since air plasma surface modification of polymers for adhesion is of high importance for various industrial usages [29].

5. CONCLUSIONS

We have seen that DIPT can be used extensively and precisely to measure different plasma parameters like density, temperature, energy, etc. of the system. We can easily understand that the rate of diffusion of the plasma is high from the energy plot itself. This is also self explanatory as the plasma is highly collisional and unconfined. From the density distribution profile we can conclude that the plasma is not homogenous and a marked difference is observed in the color profile indicating the plasma to be multi component plasma. Moreover, it can also be mentioned that the different species have different ionic energies of excitation.

A more detailed study regarding the spectral line ratio values and more refinement using Doppler broadening is required, which will give us a better estimation of the nature of the energies of the ionic species. Also, a refined algorithm for color sensitivity and modification in the image capturing technique using neutral density filter will improve the quality of the post processed values. A complete analysis of the variation of the energies and spectral profile at different discharge voltage will help us in knowing the processes of discharge with increasing voltage. The infrared imaging analysis will be a very good prospect to understand the initial stages before stable plasma is formed. IPT provides a very optimistic diagnostic tool to investigate different plasma phenomenon.

Overall, we would like to conclude that DIPT can be used as a very powerful, effective and non-invasive probing technique for investigations of different plasma phenomena.

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