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Research Paper

Development of a Plasma Training Lab kart: System Setup and Numerical Simulation

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Abstract A mobile lab kart for plasma training is developed with a high vacuum pumping system, vacuum gauges and a glass discharge tube powered by a high voltage transformer connected to a household 60 Hz line. A numerical model is developed by using a commercial multiphysics software package, CFD-ACE+ to analyze the experimental data. Simulations for argon and nitrogen were carried out to provide fundamental discharge characteristics. Variations of the kart configuration were demonstrated: a glass tube with three electric probes, optical emission spectrometer attachment and infra red thermal imaging system to give more detailed analysis of the discharge characteristics.

Keywords: Plasma, Geissler tube, CCP, Numerical simulation

I. Introduction

Plasma technology is widely used in industry ranging from microelectronics device manufacturing to surface treatment of automobile parts [1,2,3]. There has been a need to train engineers in these fields. Most of related university departments developed one or two undergraduate classes on plasma physics or introductory course to applications. High voltage engineering and nuclear engineering departments are most related ones. Some societies, e.g. American Vacuum Society, Joint Committee of European Surface Engineering and Korean Vacuum Society, have been running a short course on plasma science and technology at the conference sites. Most of these courses are class room lectures without lab hours. Plasma education should include hands-on experience of plasma generation systems. Semiconductor fabrication and surface treatment equipment are expensive to be used in college classes. A mobile kart for this purpose is developed for undergraduate level class. It includes a turbo molecular pump (56 liter/sec, 4.5 inch CF flange) and a diaphragm pump. A full range gauge is connected to the electronic display and control unit. A 2.75 inch manual gate valve is used to isolate the plasma region or to control the conductance. A glass tube (Geissler tube) is used as a discharge chamber. For economic reason, a high voltage transformer (1:68 ratio, maximum output 15,000 Vac) is connected via a slidac (input 220 Vac, output 0~220 Vac) and used as a power source to a Geissler tube. Many variations of the tube are possible: a tube with three additional electrodes placed between the two main electrodes, tubes with various electrode gaps and tube with different electrode materials. A stick with a small permanent magnet would be used to display the effects of magnetic fields on the discharge. Numerical simulation of this simple discharge tube will be useful in teaching by analyzing fundamental properties: electron temperature, electron density, electric potential, volumetric charge and chemical species distribution in the discharge tube. In this study, Ar was used as a standard gas representing atomic gases and nitrogen was used to represent molecular gases which would produce many kinds of dissociated radicals and ions. In exact manner, 3D simulation should be applied to this T-shape discharge tube system. Due to unbearable extended CPU time, a 2D-axisymmetric model is used, instead of 3D. Currently, this lab kart can only drive CCP (capacitively coupled plasma) mode. ICP sources are very useful in high density plasma processing equipments [4,5].

II. Experiment and Simulation Setup

A vacuum and plasma training purpose kart is shown in Fig. 1. A turbo molecular pump and a diaphragm pump are used to pump down and to control the vacuum level of the reactor by a manual gate valve. A T-shape glass tube is connected via an o-ring seal at the top of a cross type 2.75 inch CF flange.

Numerical simulation is done by ESI's CFD-ACE+ package. CFD-ACE+ is multiphysics based simulation software including: gas flow dynamics, heat transfer, chemistry, plasma and electromagnetic field analysis. CCP

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Figure 1. A lab kart designed for plasma education.

(capacitively coupled plasma) requires very strict numerical environments: mesh geometry, solver tuning and well defined chemical reaction database. The length of the tube is 170 mm and the diameter, 18 mm. The gap between two electrodes is 150 mm (face-to-face). The total number of the generated cells is around 10,000 as shown in Fig. 2. A coarse grid model has 2,000 cells and was used in some limited cases. A finer cell model sometimes would save CPU time by stable convergence. A drift-diffusion model is used and the numerical formulation is published elsewhere [6,7,8]. The driving frequency was 60 Hz, commercial household power frequency. In numerical simulation, low frequency means huge extended CPU time. In this study, 13 MHz was substituted for 60 Hz. As this unit is run continuously, the underlying physics is very similar. Usually, a high frequency rf period is divided by at least 40 time steps which is equivalent to 20 ns. In order to get a well converged solution, several hundred rf periods are necessary which would be several tens of thousands of time steps. Especially, much slowly varying variables, e.g. gas flow, would not make a converged solution within the rf time steps. CFD-ACE+ is using independent dual time step strategy. Slow variables are using larger time step, e.g. 10 micro seconds and only rf related variables are marching in the small time steps. This would save CPU time and reduce the possibility of divergence at the initial time steps where gas flow and other macro variables are not in reasonable value ranges.

III. Results and Discussion

1. Ar discharge simulation

The electron temperature profile of Ar discharge is shown in Fig. 3. Two opposing electrodes are driven in phase difference of 180 degree. The region around the electrodes has 8 eV of period averaged value. The electron density showed a peak at about 3 cm away from the electrode in Fig. 4. At 100 mTorr of Ar, 200 V driving voltage deposited very small amount of rf power. At 500 V, 1 W was transferred to the discharge volume via electrons and ions by Ohmic heating. In Fig. 5, the period averaged power absorption profile is shown and two distinct regions are the main area of power deposition: center region and 2 cm away from the electrode surface. The peak value was 1.8×10^4 W/m3. The edge of the electrodes absorbed slightly more power than surroundings. In experiments, it induces localized discharge or arcs at high power and high

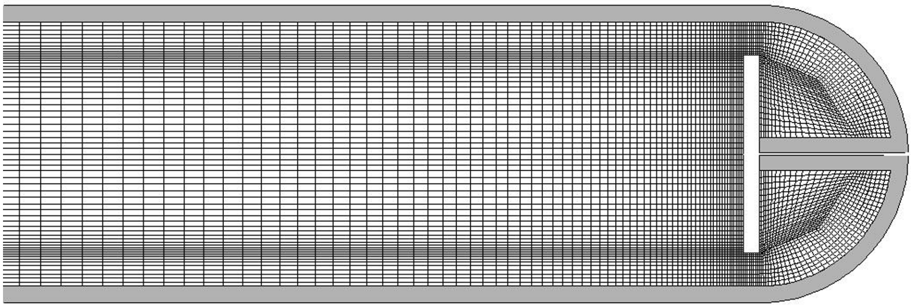

Figure 2. A numerical model developed for a glass tube discharge system.

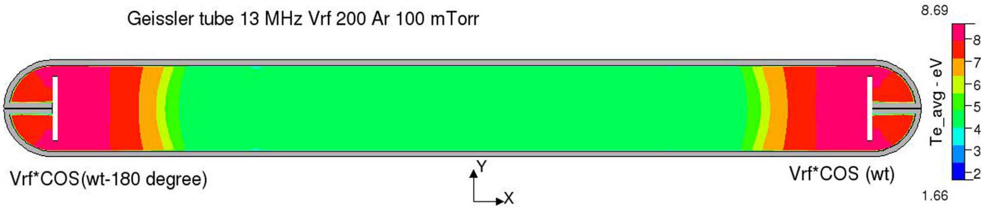

Figure 3. RF period averaged electron temperature profile of Ar discharge driven by 13 MHz at 100 mTorr.

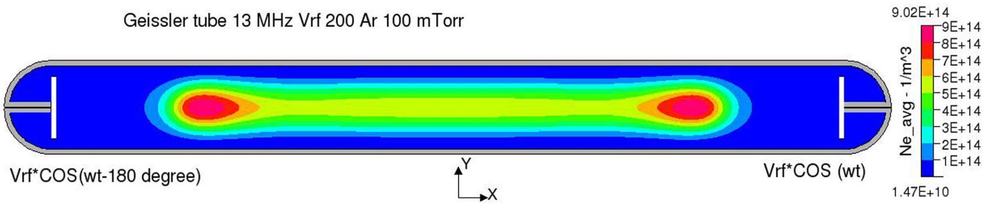

Figure 4. Electron density distribution of Ar discharge of Fig. 3.

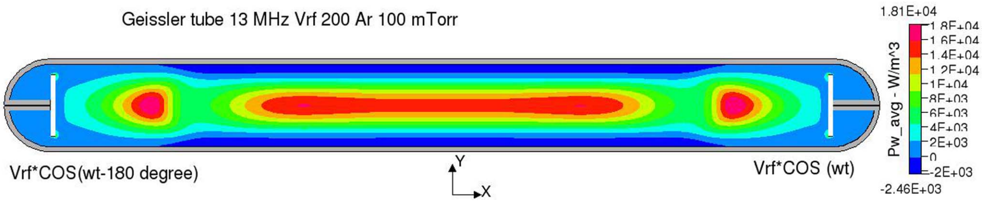

Figure 5. RF power absorption profile of Fig. 3.

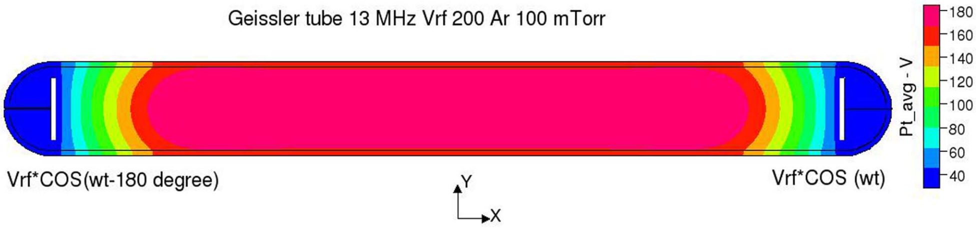

Figure 6. Electric potential profile of Fig. 3.

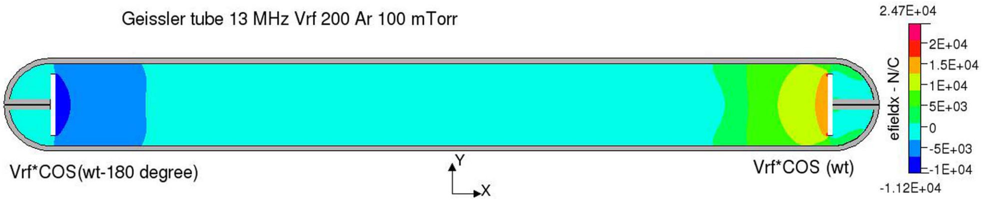

Figure 7. Axial electric field profile of Fig. 3.

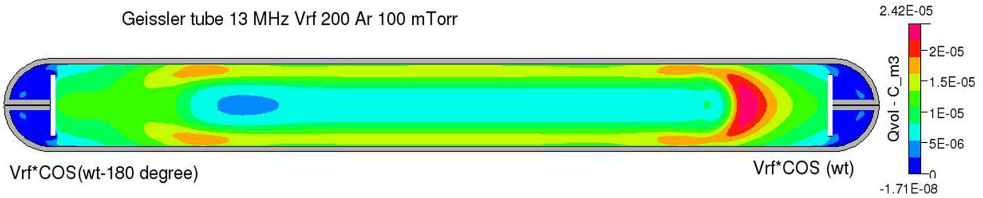

Figure 8. Volume density of space charge distribution of Fig. 3.

gas pressure conditions. Commercial Geissler tubes are hand-made by glass craftsmen. The two electrodes are often not in perfect parallel. The gap between the electrode edge and the inner surface of the glass tube is sometimes not equal. This uncertainty induces localized discharges. Numerical model only deals with perfect axi-symmetric geometry and excludes this possibility.

The electric potential profile of the discharge is calculated as shown in Fig. 6. The calculated sheath thickness would be around 12 mm which can be observed and compared by students operating this lab kart system. The glass envelope has zero surface charge boundary condition in this model. The axial electric field distribution is shown in Fig. 7. It is shown that on the electrode surface, the maximum electric field is about 15 kV/m. CFD-ACE+ provides space charge density profile as in Fig. 8. The backside region of the electrodes has negative charge density and the right electrode induced positive charge density region at 1.2 cm away from the electrode surface having peak value of 2.4×10^{-5} C/m3. Ar ion number density has two symmetric peaks at 3 cm away from the electrodes in Fig. 9. Ar metastables are spread more than ions, because they are neutrals and free from the electric field (Fig. 10). The most representative feature of the discharge system is electron's behavior. In Fig. 11, a 2D presentation and the axial graph of the electron density are shown. Even though, there is only one ionic species, Ar+, the shapes of electron density and that of the ion density

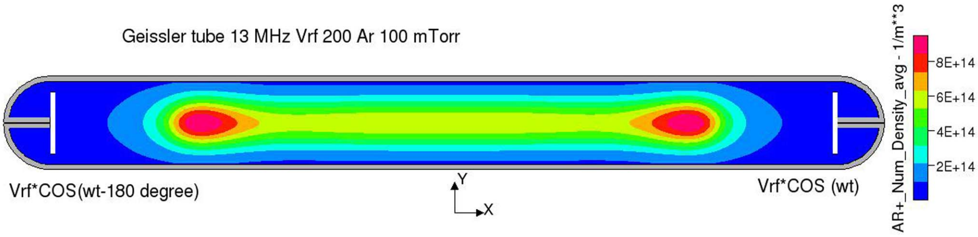

Figure 9. Ar ion number density distribution of Fig. 3.

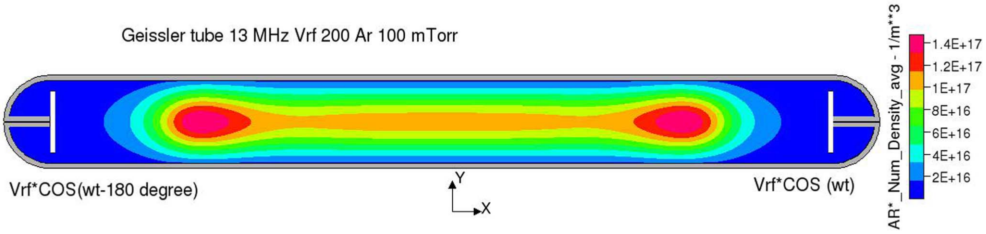

Figure 10. Ar metastable density distribution of Fig. 3.

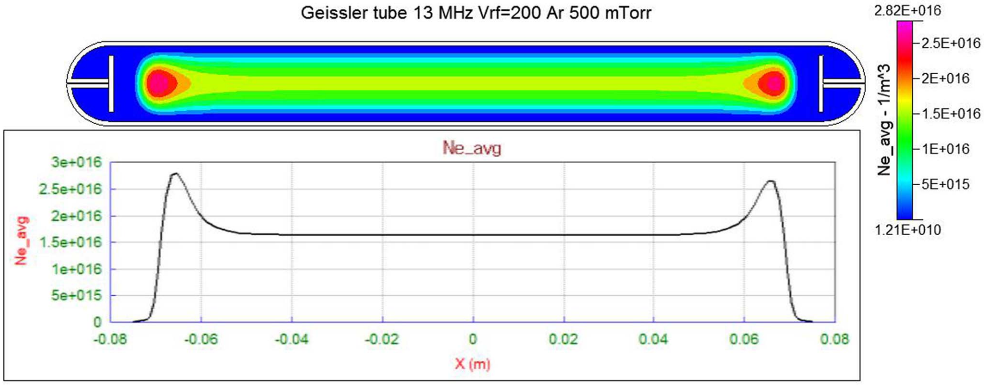

Figure 11. Electron density profile and the axial graph of Ar at 500 mTorr driven by 13 MHz.

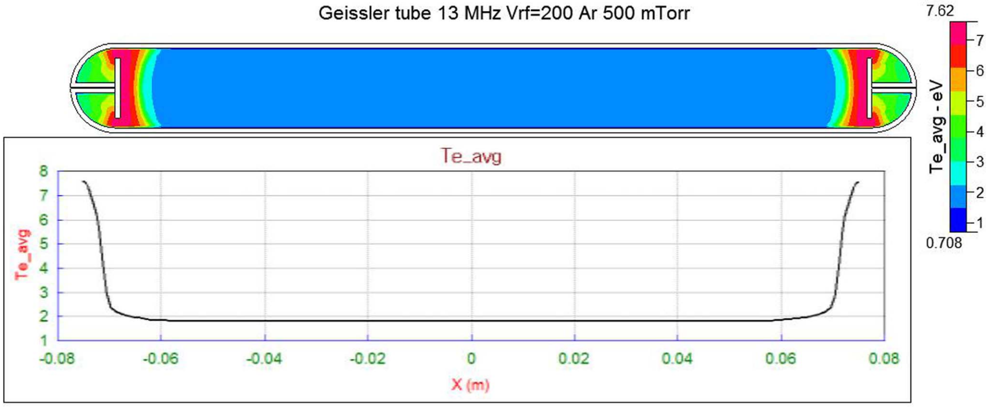

Figure 12. Electron temperature profile and the axial graph of Ar at 500 mTorr driven by 13 MHz.

are not identical. Under drift-diffusion approximation, electron has limited diffusion by positive charged particles (ambipolar diffusion). Electron-neutral collision properties are affecting on the spatial profile and will be a strong function of gas pressure and composition. Data of Fig. 9 is obtained at 100 mTorr of Ar background and that of Fig. 11 is at 500 mTorr. The higher pressure would give more localized charged particle density profile. Fig. 12 shows the electron temperature profile and the axial graph of Ar discharge at 500 mTorr and the peak value is lowered by 0.4 eV from that of the discharge at 100 mTorr. In the bulk region, the average electron temperature is about 1 eV.

2. Variation of the kart configuration

This lab kart system can switch the discharge gases other than Ar. In Fig. 13, nitrogen is modeled and calculated to give more diffuse electron distribution than that of argon. Many textbooks are mentioning discharge ignition

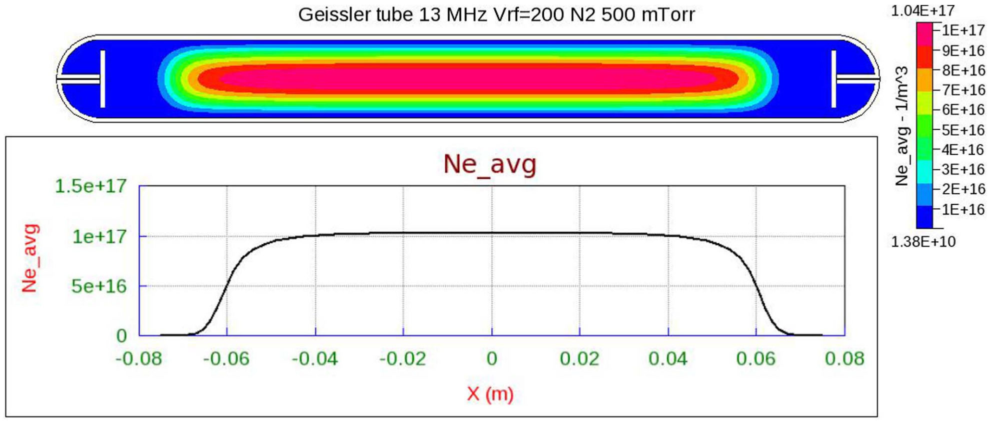

Figure 13. Electron temperature profile and the axial graph of N_2 at 500 mTorr driven by 13 MHz.

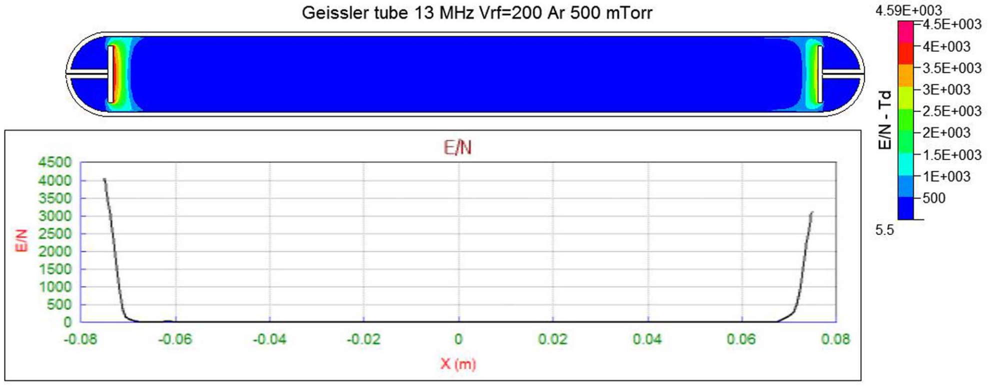

Figure 14. Electric field/particle density profile of Ar at 500 mTorr.

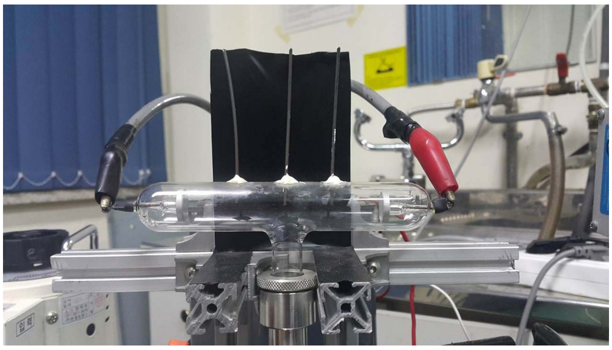

Figure 15. A variation of the lab kart with three electric probes.

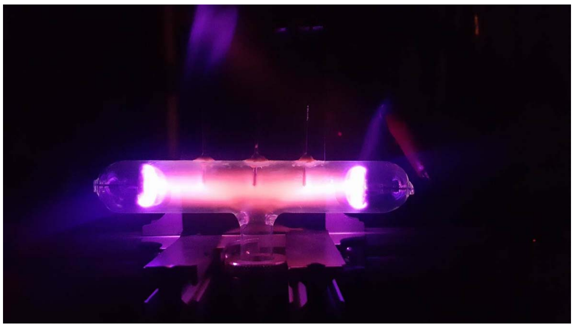

Figure 16. Discharge of the modified glass tube with three electric probes.

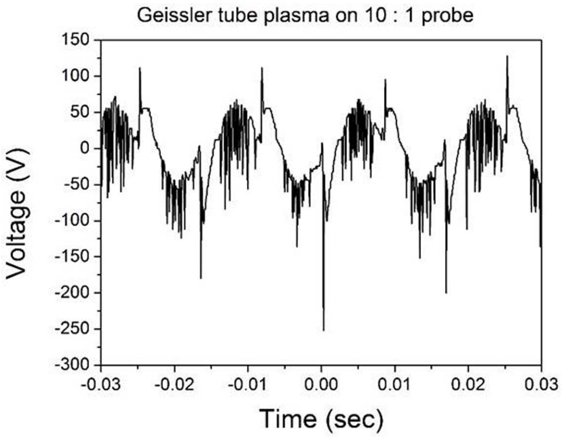

Figure 17. Measured voltage data by an oscilloscope with 10:1 attenuated probe to the three probe discharge tube.

condition as Paschen's law. The E/N (electric field/particle density) is the key factor to understand it. Fig. 14 is showing E/N profile for Ar discharge at 500 mTorr. It gives maximum of 4,590 V*m2 and the bulk value is less than 5.5. The calculated result proves the fact that the plasma bulk region is almost field free.

The lab kart can be reconfigured into many ways. One of them is a modified Geissler tube with probing electrodes as shown in Fig. 15. Those electrodes can be used as a probe or a powered electrode to ignite the discharge. Fig. 16 is showing the discharge photo of it. The voltage versus time data were taken from the left most probe and shown in Fig. 17. After extended operation of this glass enveloped tube,

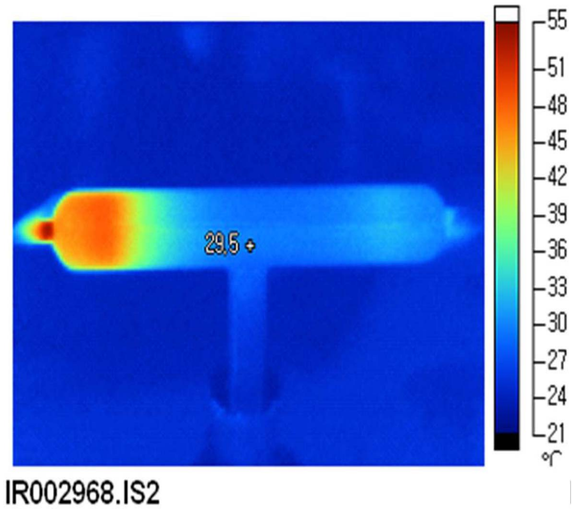

Figure 18. Infra-red thermal image of the discharge tube after operation.

electron and ion heating would increase the surface temperature of the glass tube. In Fig. 18, a tube with dc powered configuration is showing the cathode region is heated up to 55°C after some time. For educational purposes, additional analysis tools, e.g. optical emission spectrometer can be configured as shown in Fig. 19. Detailed analysis of the spectra would be helpful in training students. It will give them engineering concepts of end point detection, impurity analysis and plasma uniformity.

IV. Conclusions

A mobile lab kart is designed to give hands-on experiences to trainees in plasma science and technology classes. A small turbo molecular pump backed by a diaphragm pump is used to give oil free environment. All are air cooled, so no need of cooling water connection. Glass tube discharge system is adopted and powered either by a household 60 Hz ac or dc. A simple version is equipped with a high voltage transformer and a slidac. A numerical model is developed to help this lab kart's usability by using a commercial multiphysics simulation package, CFD-ACE+. The calculated results showed very useful data in understanding the basics of plasma generation and characteristics. Variation of discharge tubes, addition of analysis system was demonstrated to give atomic spectra and infra red image based temperature distribution.

Acknowledgements

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References

[1] Y. Yoo and J. Joo, J. Kor. Inst. Surf. Eng., Vol. 46, No. 4 (2013) 168.
[2] J. Joo, Kor. Inst. Surf. Eng., Vol. 46, No. 3 (2013) 133.
[3] J. Joo, Kor. Inst. Surf. Eng., Vol. 45, No. 2 (2012) 53.
[4] S. Lee, J. Kor. Vac. Soc., Vol. 18, No. 3 (2009) 176.
[5] D. Kwon and N. Yoon, Appl. Sci. Conv. Technol., Vol. 24, No. 6 (2015) 237.
[6] H. Kim, W. Yang and J. Joo, J. Appl. Phys. Vol. 118, (2015) 043304-1.
[7] J. Joo, Thin Solid Films, Vol. 519 (2011) 6892.
[8] S. Son, K. Yi and J. Joo, J. Mahrholz, and K. Rie, J. Cry. Growth, Vol. 310 (2008) 1697.
[9] J. Joo and S. Rossnagel, J. Kor. Phys. Soc., Vol. 54 (2009) 1048.
[10] J. Joo, Appl. Sci. Conv. Technol., Vol. 24, No. 4 (2015) 102.
[11] J. Joo, Appl. Sci. Conv. Technol., Vol. 23, No. 3 (2014) 139.
[12] J. Coburn and M. Chen, J. Appl. Phys, Vol. 51 (1980) 3134.

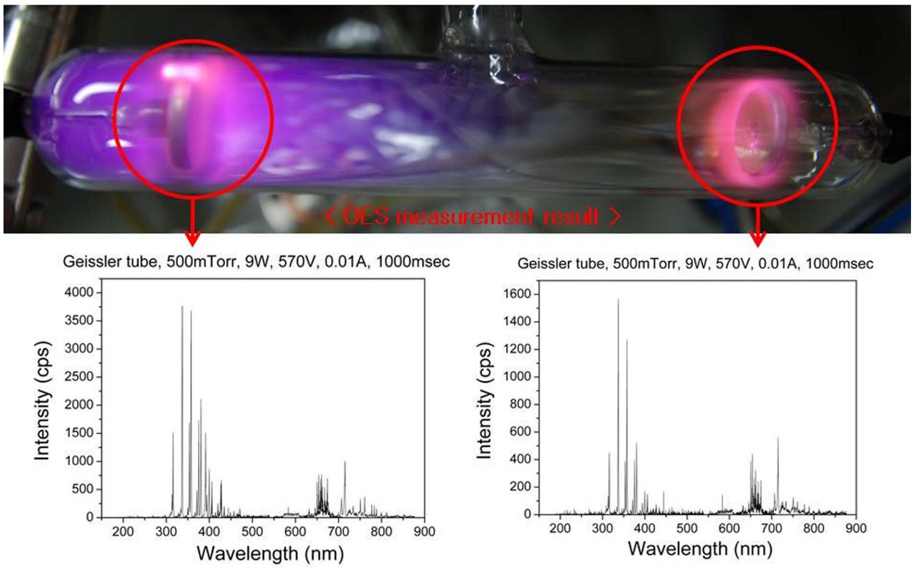

Figure 19. Optical emission spectra obtained at the two extreme position of the discharge tube.