Report on Visit to the Queen's University Belfast, UK by International Training Program

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1. Introduction

I studied about electron temperature measurement of liquid plasma with optical emission spectroscopy at Professor Graham's Laboratory in Queen's University Belfast (QUB) by using International Training Program. The duration of the stay in QUB was from 5th November 2012 to 8th January 2013. The summary of the stay is reported below.

2. Queen's University Belfast

Belfast is the capital and main city of Northern Ireland for its high level culture and industry. The city has a population of more than 270,000. Shipbuilding has been one of main industries for long time. The Titanic which is famous for a movie was built by Harland and Wolf which is a heavy industry company based in Belfast. Aviation industry is also prospering today. In japan it's infamous for the Northern Ireland Troubles or 2011 terrorist incidents, but is not so unsafe for foreign students or tourists.

Fig.1. Queen's University Belfast.

QUB is a public research university chartered in 1845 by Queen Victoria with its own proud academic history for about 170 years. The university is a member of the Russell Group of 24 leading UK research-intensive universities, providing world-class education underpinned by world-class research. With more than 17,000 students, 3,500 staff and up to 1,200 foreign students from over 70 countries, it makes a major contribution to medical science, economy, industry and culture in Northern Ireland and global community.

Centre for Plasma Physics (CPP) where I attended is affiliated to School of Mathematics & Physics works to advance understanding of plasma physics. The main research theme are non-thermal plasma, high-power laser produced plasma, fundamental atomic, molecular and optical processes and applications of ionizing radiation and plasmas in medicine and biology.

The main campus is located in the distance for 15 minutes on foot from the Belfast city hall.
There's a residential area and green around the university while there are many restaurants, café and supermarkets, so it is useful and suitable for students to live

3. Research activity

I studied an optical measurement of electron temperature plasma inside bubbles under high-conductivity solution at CPP.

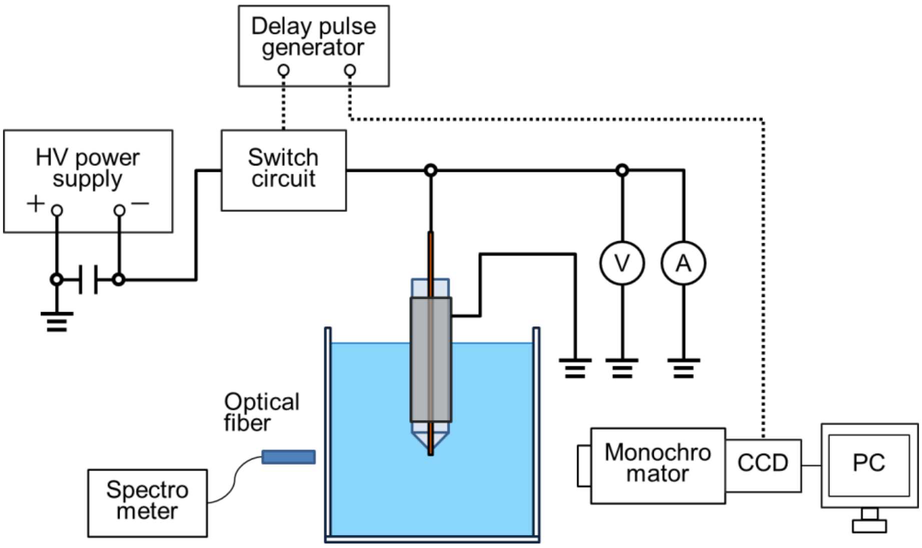

Fig.2. Experimental apparatus.

Recently, much attention has been given to plasmas generated inside bubbles under liquids due to its high potential for a variety of material processing, environmental and biomedical applications. However, due to difficulty in diagnosing the plasmas, basic research to understanding the reaction process is still open problem.

This research aims to understanding of characteristics and mechanism of discharges in high-conductivity solutions by using optical emission spectroscopy

Fig.2 shows schematic of experimental apparatus. Electrical connections are shown as solid black lines and data transmission is indicated in dotted lines. The electrode setup consists of a powered tungsten electrode of 0.5 mm diameter which is partially inserted in a quartz glass capillary, leaving the tip exposed. A ring shaped return electrode is fitted to the outside of the capillary. Powered and earthed electrodes are immersed in a solution of 1.8% w/v $BaCl_2$ in deionized water.

Pulsed power (voltage: -300 V, width: 250 μs, repetition frequency: 50 Hz) is applied to electrodes and produce a bubble and discharge in solution. This high-voltage pulse is produced by a DC power supply via a transistor circuit. Optical signals are detected by a spectrometer and a monochromator with ICCD camera. The generated voltage and current pulses are analyzed using a voltage probe and current probe respectively. The trigger signal to operate the transistor circuit and ICCD camera is generated using a delay pulse generator.

Fig. 3 shows typical waveforms of trigger pulse, current and voltage. The current decreased while the voltage increased from the pulse initiation to roughly 60 μs. The decreasing current means increasing system resistivity due to gas layer of water vapor surrounding the tip of the electrode generated by Ohmic heating. At 60 μs, the current increased rapidly while the voltage decreased. Discharge can be generated inside a bubble at that time.

The simplest case for spectroscopic measurement of electron temperature is to assume that electrons have a Maxwellian temperature distribution in LTE plasma. In optically thin plasmas of length l along the line of sight, spectrally integrated emission line intensities are

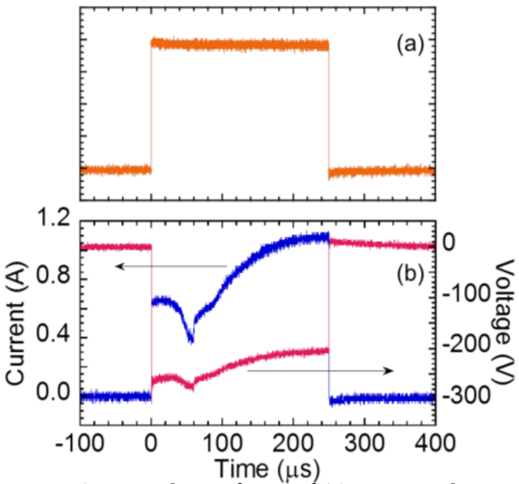

Fig.3. Typical waveforms of (a)Trigger pulse (b)Current and Voltage.

given by

$$i_{nm} \approx \frac{hcl}{4\pi}\frac{A_{nm}}{\lambda_{mn}}N_m$$

Where ω_{mn} is the frequency of the photon, A_{nm} is the transition probability and N_m is the electron population of the state m. From the Boltzmann equation, N_m is described by

$$N_m = N g_m \exp\left(-\frac{E_m}{k_B T_e}\right)$$

Using this equation, the line intensities can be written as

$$i_{nm} \approx \frac{hclN}{4\pi}\frac{A_{nm}g_m}{\lambda_{mn}}\exp\left(-\frac{E_m}{k_B T_e}\right)$$

Where N is the total population of electrons, g_m is the statistical weight of the state m, E_m is the energy of the state and T_e is the electron temperature. Using this in combination with the previous equation the line ratios can be written as

$$R = \frac{i_{n_1m_1}}{i_{n_2m_2}} \approx \frac{\lambda_{m_2n_2}A_{n_1m_1}g_{m_1}}{\lambda_{m_1n_1}A_{n_2m_2}g_{m_2}}\exp\left(-\frac{E_{m_1}-E_{m_2}}{k_B T_e}\right)$$

This can be rearranged to give an equation in terms of the electron temperature

$$k_B T_e = \frac{E_{m_1}-E_{m_2}}{\ln\left(\frac{\lambda_{m_2n_2}A_{n_1m_1}g_{m_1}}{\lambda_{m_1n_1}A_{n_2m_2}g_{m_2}}R\right)}$$

The relative error in the temperature is given by

$$\left|\frac{\Delta T_e}{T_e}\right| = \frac{k_B T_e}{E_{m_1}-E_{m_2}}\left|\frac{\Delta X}{X}\right|$$

X is all terms in the argument of the logarithm.

In dense LTE plasmas of known electron density, this measurement can apply to ion line intensities. Using the Saha's ionization equation

$$\frac{N_e N_i}{N_0} = \frac{2g_i}{g_0 {a_0}^3}\left(\frac{k_B T_e}{4\pi E_H}\right)^{\frac{3}{2}}\exp\left(-\frac{E_I}{k_B T_e}\right)$$

the line intensities from ion can be written as

$$i_{nm} \approx \frac{hclN}{4\pi}\frac{A_{nm}g_m}{\lambda_{mn}}\frac{2g_i}{{a_0}^3 N_e}\left(\frac{k_B T_e}{4\pi E_H}\right)^{\frac{3}{2}} \times \exp\left(-\frac{E_I + E_m}{k_B T_e}\right)$$

Fig.4 shows typical time-averaged spectra of this plasma. Table 1 shows barium spectra data corresponding to emission lines (Fig.5) from the NIST atomic line spectra database. Most of the spectra were from Ba^{1+} ion lines. The line.9 which has two lines overlapped each other was measured by using a higher-resolution monochromator to separate the lines.

Fig.5 shows ion line intensities normalized by an atomic line.6 $(i_{nm}/i_{No.6})/(A_{nm}g_m/\lambda_{mn})$ versus electron energy $E_I + E_m$ (eV). Approximating an exponential function, the inverse of the slope indicates electron temperature

$$T_e = 0.87 \text{ eV}$$

However, the plots were not completely on the approximation line. This suggests that

- LTE or Maxwell-Boltzmann distribution of one temperature is not applied because of low electron density in atmospheric-pressure plasmas (N_e: 10^{19}~10^{20} m^{-3})

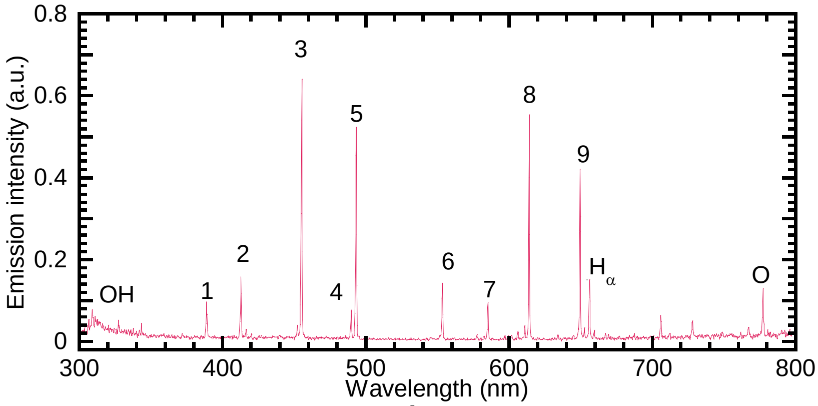

Fig.4. Time-averaged emission spectra.

Table1. Ba spectra data.

No.		λ (nm)	A (s^{-1})	Ei(eV)	Ek(eV)	Lower Level			Upper Level			gi	gk
1	Ba II	389.18	2.17E+08	2.512113	5.697008	6p	$^2P^o$	$^1/_2$	6d	^2D	$^3/_2$	2	4
2	Ba II	413.06	2.18E+08	2.721751	5.722471	6p	$^2P^o$	$^3/_2$	6d	^2D	$^5/_2$	4	6
3	Ba II	455.40	1.11E+08	0.000000	2.721751	6s	^2S	$^1/_2$	6p	$^2P^o$	$^3/_2$	2	4
4	Ba II	489.99	1.04E+08	2.721751	5.251372	6p	$^2P^o$	$^3/_2$	7s	^2S	$^1/_2$	4	2
5	Ba II	493.41	9.53E+07	0.000000	2.512113	6s	^2S	$^1/_2$	6p	$^2P^o$	$^1/_2$	2	2
6	Ba I	553.55	1.19E+08	0.000000	2.239187	$6s^2$	^1S	0	6s6p	$^1P^o$	1	1	3
7	Ba II	585.37	6.00E+06	0.604281	2.721751	5d	^2D	$^3/_2$	6p	$^2P^o$	$^3/_2$	4	4
8	Ba II	614.17	4.12E+07	0.703586	2.721751	5d	^2D	$^5/_2$	6p	$^2P^o$	$^3/_2$	6	4
9	Ba II	649.69	3.10E+07	0.604281	2.512113	5d	^2D	$^3/_2$	6p	$^2P^o$	$^1/_2$	4	2
	Ba I	649.88	5.40E+07	1.189818	3.097105	6s5d	^3D	3	5d6p	$^3D^o$	3	7	7

- In plasma which has dens barium ion compared to barium atomic density, not only ionization excitation of atoms but also excitations of ions and light absorption due to resonance lines of barium such as line.3 and line.5 must be considered.

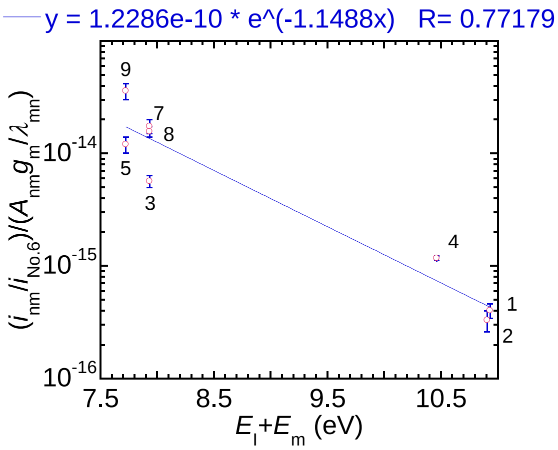

Fig.5. Emission intensity ratio plotted as a function of electron energy.

4. Summary

During my stay in QUB for two month, I could study the spectroscopic measurement of electron temperature in high-conductivity solution plasma. It was a precious experience for me because I could learn and acquired knowledge of optical and liquid plasma physics and measurement.

Finally, I would like to appropriate Prof. Graham, all staff and students they help me so much in QUB. I also appreciate Prof. Hori, Prof. Toyoda and secretary of ITP office for supporting my visiting.