

# **Final Report**

on

## **Study of Cryogenic Complex Plasma**

**AOARD 074047**

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## Report Documentation Page

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14. ABSTRACT

**Overall goal is to study basic physics of a complex plasma at a room temperature as well as in a cryogenic environment and to reveal novel natures of a cryogenic complex plasma produced by a stable discharge above or in super fluid liquid helium . This final report describes a research carried out at the Complex Plasma Lab on Complex plasma, also known as dusty plasma and plasma with micron-sized dust particles in which charged dust particles interact with background plasma. A system with dust particles is characterized by low frequency oscillations, 1 to 10 Hz, and a system with plasma particles is characterized by high frequency oscillations, 0.1 to 10GHz. The interaction between two distinct systems produces novel features in cooperative phenomena. Basic features of complex plasma at a room temperature have been studied by a device YCOPEX, while cryogenic complex plasma has been studied by YD-1 and YD-2. Researchers have produced discharge plasma in the vapor of liquid helium in the device YD-2 and in the helium gas cooled by liquid helium in the device YD-1. Two Dewar bottles accommodate cryogenic plasma with dust particles. In YD-1, cryogenic RF plasma is produced in a helium gas in a glass tube surrounded by cryogenic liquid (liquid nitrogen or liquid helium) and dust particles are introduced in the plasma. In YD-2, a cryogenic plasma is produced in the vapor of liquid helium above the super fluid liquid helium. Stable complex plasma in a cryogenic environment has been produced successfully in YD-1 as well as in YD-2. A linear device YCOPEX (Yokohama Complex Plasma Experiment, installed in the summer, of 2006) has been used to study the fundamental physics of room temperature complex plasma. Theoretical study on Coulomb clusters by dust particles revealed the CME (configuration of minimum energy) structures for elongated plasma confinement. Theoretical and simulation study on cryogenic complex plasma has revealed the diffusion process of charged dust particles produced in the vapor of liquid helium toward the surface of liquid helium.**

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## ABSTRACT

This final report describes a research on the contract of investigation entitled by “Study of Cryogenic Complex Plasma” (Principal investigator: O. Ishihara, FA4869-07-1-4047, AOARD 074047, June 26, 2007 - June 25, 2008). The research has been carried out at the Complex Plasma Lab of Yokohama National University in Yokohama. Research personnel includes a principal investigator Osamu Ishihara, a senior technical advisor Dr. Yoshiharu Nakamura, a research associate Dr. Masako Shindo, doctoral students Mr. Chikara Kojima and Mr. Wataru Sekine. Several graduate students as well as senior undergraduate students were also involved in the experiments.

Complex plasma, also known as a dusty plasma, is a plasma with micron-sized dust particles in which charged dust particles interact with a background plasma. A system with dust particles is characterized by low frequency oscillations, typically 1 to 10 Hz, and a system with plasma particles is characterized by high frequency oscillations, typically 0.1 to 10GHz. The interaction between two distinct systems produces novel features in cooperative phenomena. Basic features of a complex plasma at a room temperature has been studied by a device YCOPEX, while a cryogenic complex plasma has been studied by YD-1 and YD-2. We have produced a discharge plasma in the vapor of liquid helium in the device YD-2 and in the helium gas cooled by liquid helium in the device YD-1. Two Dewar bottles, YD-1 (Yokohama Dewar 1, installed in April, 2004) and YD-2 (Yokohama Dewar 2, installed in September, 2004), accommodate cryogenic plasma with dust particles. In YD-1, a cryogenic rf plasma is produced in a helium gas in a glass tube surrounded by cryogenic liquid (liquid nitrogen or liquid helium) and dust particles are introduced in the plasma. In YD-2, a cryogenic plasma is produced in the vapor of liquid helium above the superfluid liquid helium. Stable complex plasma in a cryogenic environment has been produced successfully in YD-1 as well as in YD-2. A linear device YCOPEX (Yokohama Complex Plasma Experiment, installed in the summer, of 2006) has been used to study the fundamental physics of a room temperature complex plasma. Theoretical study on Coulomb clusters by dust particles revealed the CME (configuration of minimum energy) structures for elongated plasma confinement. Theoretical and simulation study on cryogenic complex plasma has revealed the diffusion process of charged dust particles produced in the vapor of liquid helium toward the surface of liquid helium.

## I. Objectives

Our overall goal is to study basic physics of a complex plasma at a room temperature as well as in a cryogenic environment and to reveal novel natures of a cryogenic complex plasma produced by a stable discharge above or in superfluid liquid helium .

## II. Research Personnel

The principal investigator, Professor Osamu Ishihara of Yokohama National University, has been conducting the research at Yokohama National University. Research personnel includes

- (1) Dr. Yoshiharu Nakamura, a senior researcher retired from the Institute of Space and Astronautical Science, who is a technical advisor for the overall program,
- (2) Dr. Masako Shindo, Research Associate, who is responsible for the YD-2 experiment,
- (3) Mr. Chikara Kojima, a doctoral student (PhD granted on June 30, 2008) who has been in charge of YD-1 experiment.
- (4) Mr. Jumpei Kubota, a graduate student in charge of YD-1 experiment,
- (5) Mr. Wataru Sekine, a doctoral student, involves in the theory/simulation study of the cryogenic complex plasma, and
- (6) Ms. Naomi Shibuya, a secretary, supports the accounting and the administrative work in the complex plasma laboratory.

A senior researcher, Professor Tetsuo Kamimura of Meijo University, collaborates with us in the theoretical/computational research on the project. Other graduate students include Mr. Yuki Tashima and Mr. Junya Okabe, and two senior students include Mr. Keita Abe and Ms. Natsuko Uotani.

## III. RESEARCH ACCOMPLISHMENTS

### (1) YD-1 Experiment

YD-1 (Yokohama Dewar 1) is a cryostat system including a Dewar vessel transferred from Niigata University in April, 2004. Major change of the overall system in Yokohama is in a discharge system. Figure 1 shows the schematic of YD-1. An rf discharge in the helium gas in a glass tube surrounded by a cryogenic liquid (liquid nitrogen or liquid helium) in the Dewar bottle produces a stable plasma. We have been successful in producing a plasma (1) in the helium gas surrounded by liquid nitrogen and (2) in the helium vapor above the liquid helium in the glass tube where the helium gas in the tube is liquefied by lowering the pressure in the tube and the tube itself is surrounded by liquid helium. Acrylic particles in the range of 1 to 10  $\mu$  m are introduced into the plasma, forming a complex system of a plasma with charged dust particles, known as a complex plasma (see Review article: O. Ishihara, Complex Plasma: Dusts in Plasma, Journal of Physics D: Appl. Phys. **40**, R121-R147 (2007)). Dust particles in a complex plasma are illuminated by a green laser light sheet (532.8nm) or a red light laser sheet (671nm) through a slit with a width of 10 mm of the Dewar bottle.

A novel technique of a prism-mirror method with a prism placed under the glass tube as shown in Fig. 1 is established to observe dust particles illuminated by a laser light. We have observed a cluster of charged dust particles levitated in a plasma.

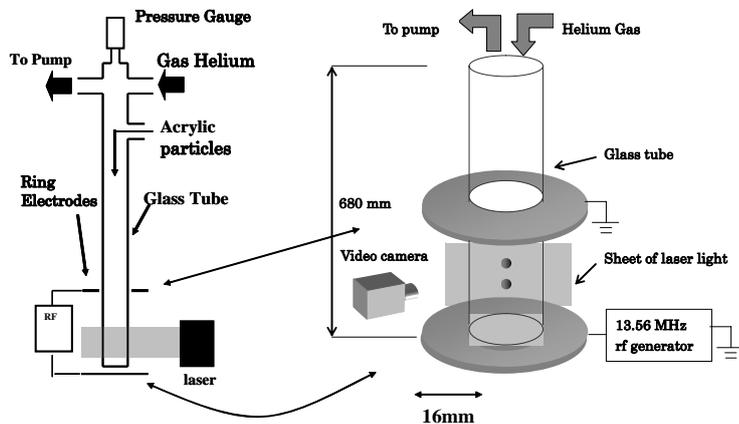
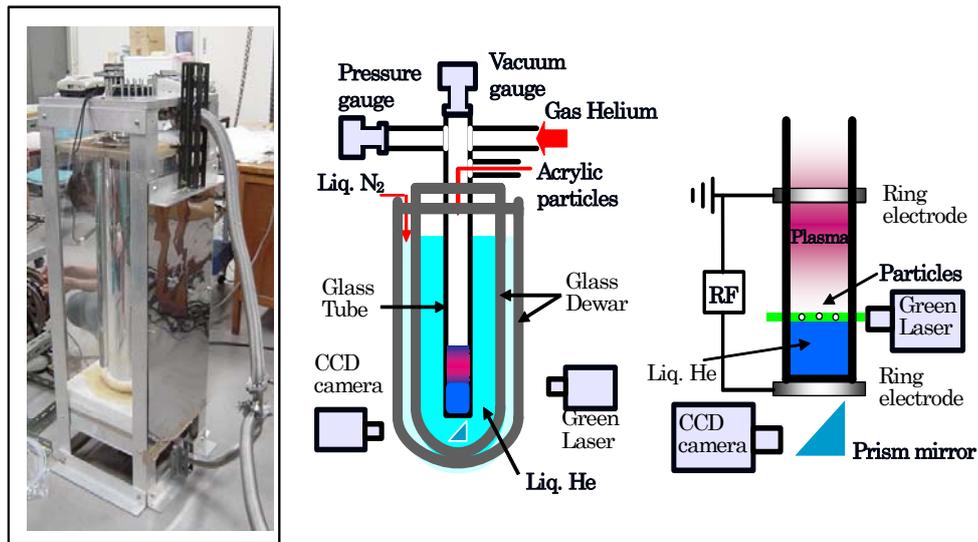
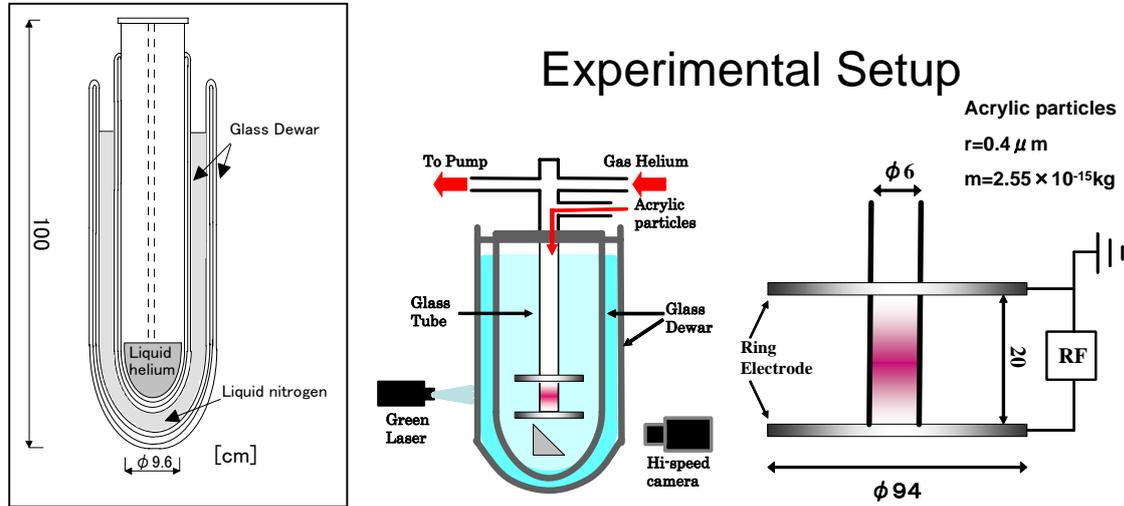


Fig. 1 YD-1 apparatus and the inner glass tube.

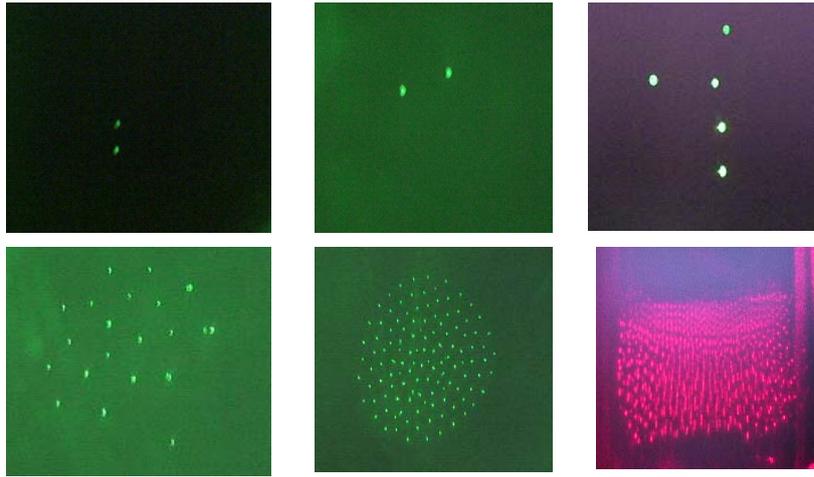


Fig. 2 Observation of dust particles in YD-1 (He gas, 300[K], 0.08~1.0[torr])

Figure 2 shows examples of dust particles photographed in YD-1. The pictures are taken at a room temperature for clear images. While we were carrying out preliminary experiments at a room temperature without surrounding cryogenic liquid, we observed peculiar behavior of dust particles in a plasma near the bottom of the glass tube. After dust particles were dropped and exposed in a plasma, charged dust particles started to move up in the plasma as shown in Figs. 3 and 4.. Dust particles were going upward against the gravity in the plasma, something not reported in the literature. We interpret now that dust particles are in a long sheath region where strong electric field exists while plasma is characterized by no electric field. Negatively charged particles were pushed upward by the sheath electric field. Although we did not plan to study dynamics of dust particles in a sheath at the room temperature, we realized that our Dewar bottle is very useful to study particle dynamics in a sheath. Because of the 1 m long tube, dust particles gain gravitational energy and dust particles could dive well into the sheath. In a conventional experimental device, which is 10 cm in vertical length at most, dust particles are stationary at the sheath edge balanced by the gravitational force and the sheath electric field. Our observation shows the dynamic motion of dust particles in the sheath region, something not reported in the past. We presented our findings at the international conference in October, 2007 in Nara.

The technique developed in the room temperature is used to determine the dust charge in the cryogenic environment. The results were reported with the title ‘Dust Charge in Cryogenic Environment’ by Mr. Jumpei Kubota in the Fifth International Conference on Physics of Dusty Plasma (ICPDP5) held in May 18-21, 2008 at Ponta Delgada, Azores, Portugal. The principal investigator, Osamu Ishihara, was invited to give a talk on our research at ICPDP5 with the invited lecture title ‘Complex Plasma Research under Extreme Conditions.’

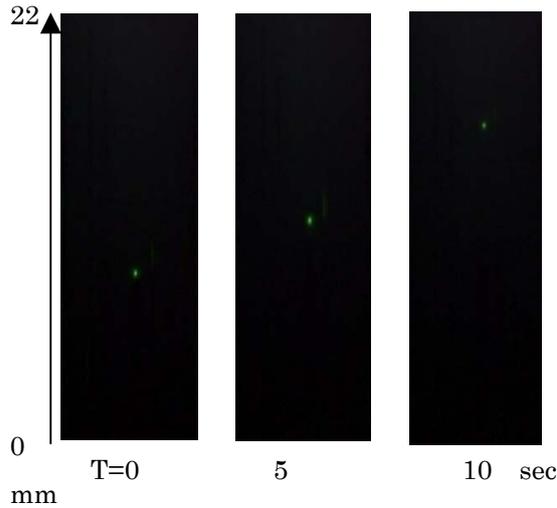


Fig. 3 A single dust motion in the sheath at pressure of 25 Pa and rf = 25W. The dust particle injected from the dust inlet move deep into glass tube at a position of  $z \approx 8.5\text{mm}$ . The dust particle move upward till  $z \approx 17\text{mm}$ .

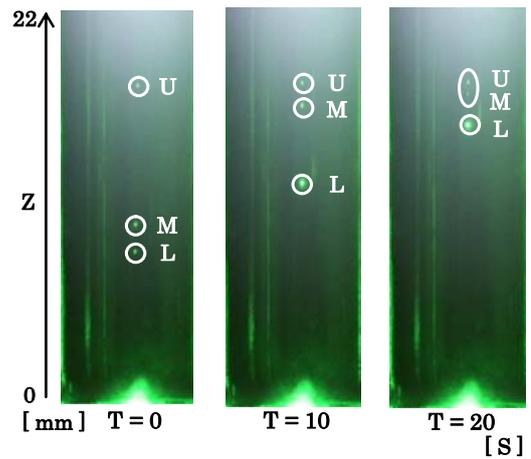


Fig. 4 Three dust motion in the sheath at pressure of 25 Pa and rf = 25W. The upper particle (U) stays at 16.8 mm from the electrode. The middle particle (M) and the lower particle (L) move upward till  $z \approx 15.2\text{ mm}$  and  $z \approx 16.2\text{ mm}$ , respectively.

Experiments of forming a complex plasma at the room temperature as well as in a cryogenic environment were carried out and the CCD camera enabled us to detect the formation of the Coulomb crystals as shown in Fig. 5.

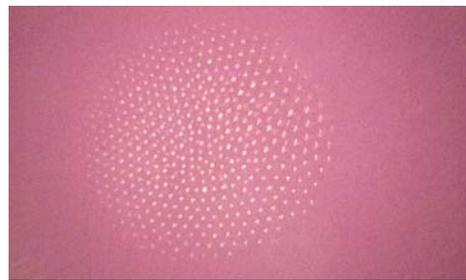


Fig. 5 CCD camera image of charged dust particles levitated and spread in a plasma in a 1.6 cm glass tube in YD-1 at 300K

## (2) YD-2 Experiment

YD-2 (Yokohama Dewar 2) , built by JEC-Tori Corporation of Saitama Prefecture for us, is a larger Dewar vessel which accommodates a discharge chamber (see Figs. 6A and 6B). It is aimed to produce a plasma in a vapor of liquid helium in a confined chamber. We have produced a plasma in the vapor of liquid helium in the discharge unit with electrodes inside and tungsten wires outside of the unit. We have observed a plasma in the device and some preliminary results with dust particles were obtained. We have developed a PIV (Particle Image Velocimetry) system to study dynamics of dust

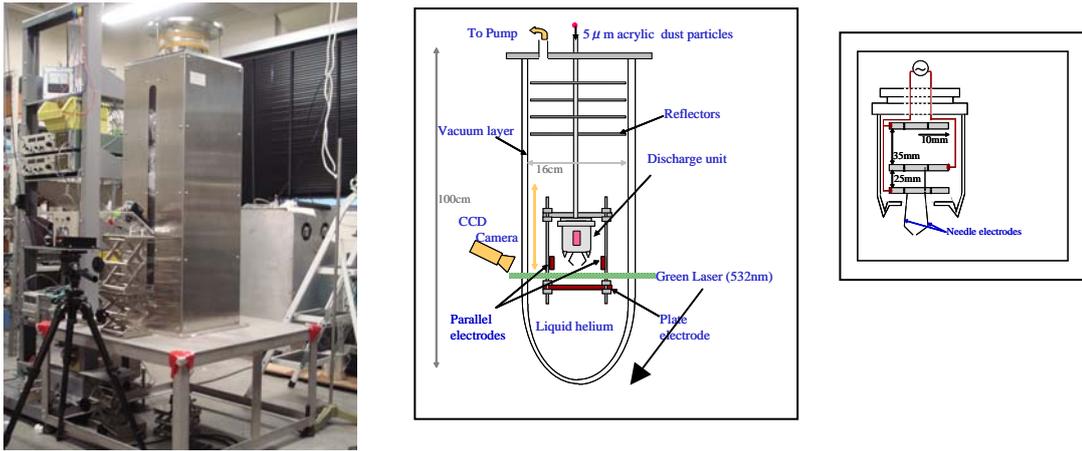


Fig. 6A YD-2 apparatus on a table. A schematic of a Dewar bottle and the inner discharge unit

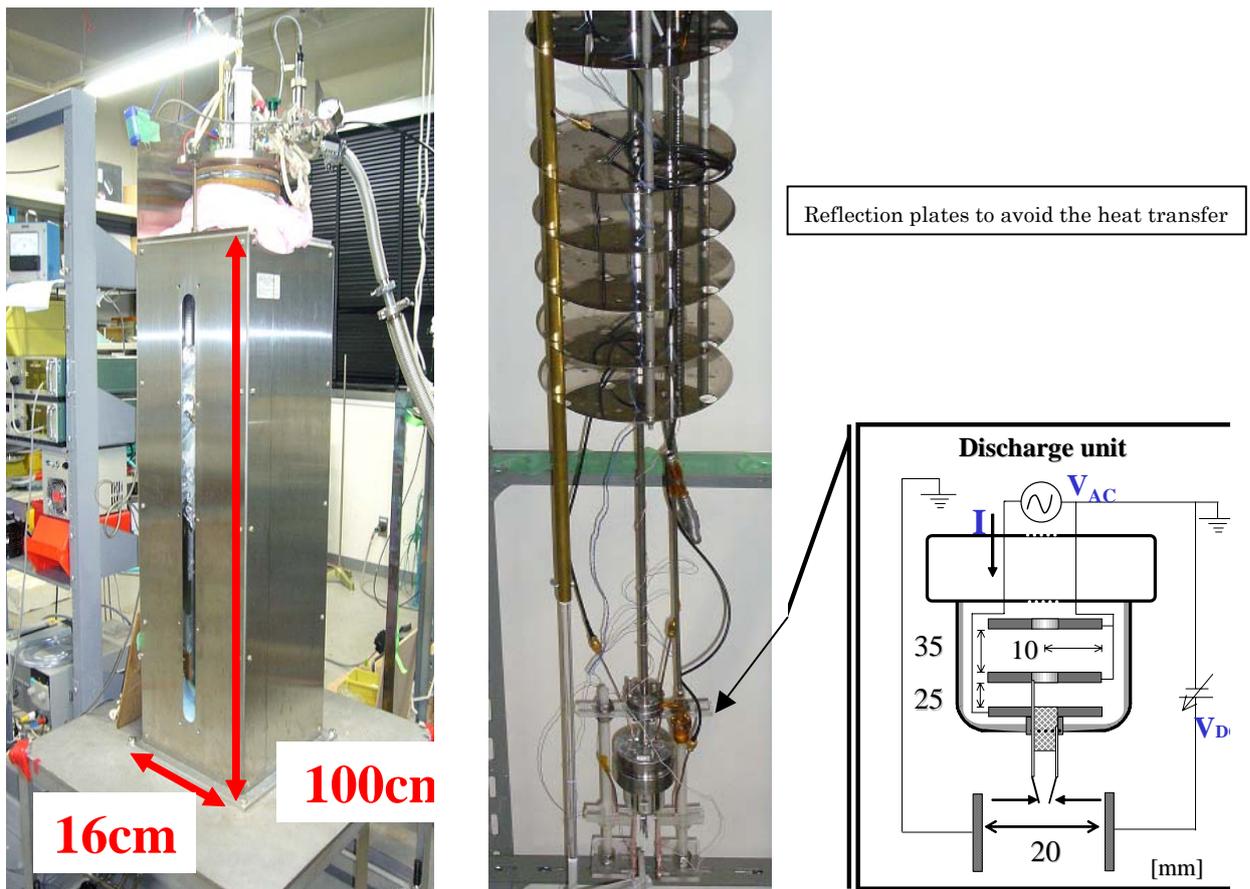


Fig. 6B YD-2 and the inner structure

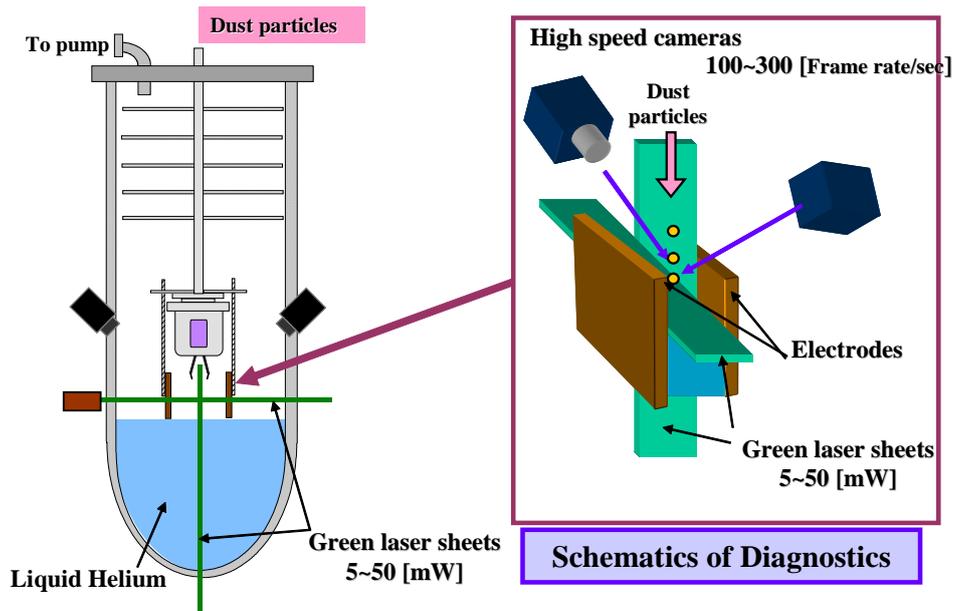


Fig. 7A Schematic set-up of PIV (Particle Image Velocimetry) system

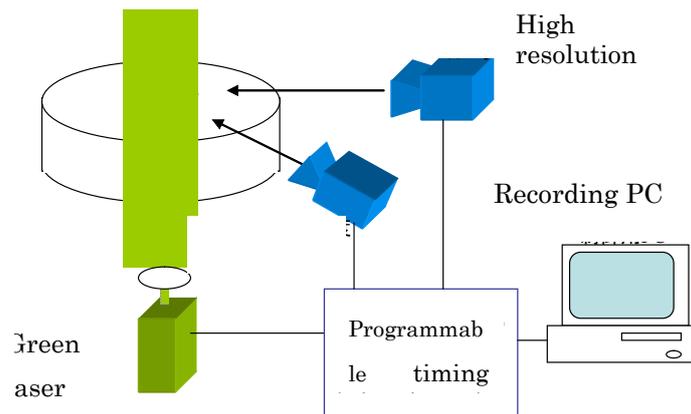


Fig. 7B Schematic set-up of PIV (Particle Image Velocimetry) system

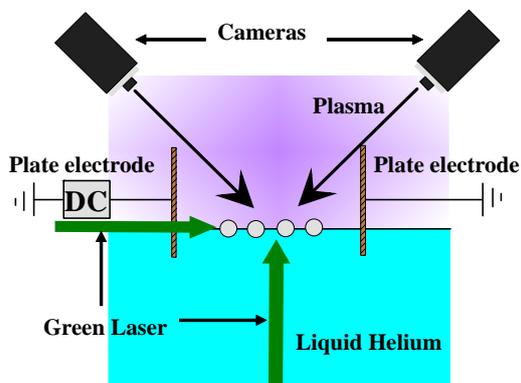


Fig. 8 Schematic set-up of laser system with two CCD cameras.

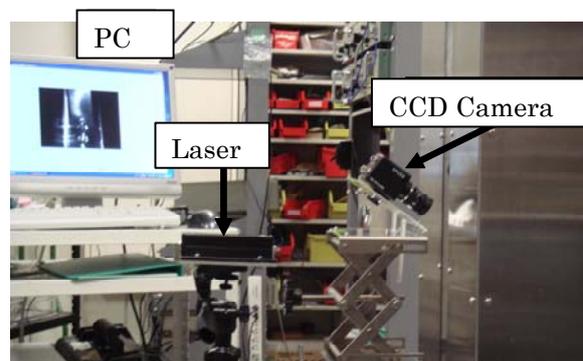


Fig. 9 Set-up of PIV system including CCD camera, laser and a recording PC.

particles in the cryogenic environment (see Figs. 7-9). The PIV system is used for monitoring particle motion of dust particles in a plasma as well as in liquid helium (Ref: R.J. Donnelly et al., *The Use of Particle Image Velocimetry in the Study of Turbulence in Liquid Helium*, J. Low Temp. Phys. 126, 327(2002), E. Thomas, Jr. et al, *Experimental Measurements of Velocity Dissipation and Neutral-drag Effects during the Formation of a Dusty Plasma*, Phys. Rev. Lett. **95**, 055001 (2005)). We reported our results at a JPS (Japan Physical Society) meeting which was held in Sapporo in September 20-23, 2007. The recent overall activities of the YD-1 and YD-2 are summarized in the article published as a book chapter in Nano- and Micromaterials (see Shindo and Ishihara (2008)).

### (3) YCOPEX (Yokohama Complex Plasma Experiment)

YCOPEX is a linear machine to make a complex plasma at the room temperature to support the YD-1 and YD-2 experiments. This simple linear machine has been built to assist the diagnostics of a cryogenic complex plasma in YD-1 and in YD-2. The 1 m long cylindrical Pyrex glass chamber with inner diameter of 16 cm, shown in Fig. 10, has been used to study fundamental physics of a complex plasma including charge state of dusts, ion and neutral drag forces on a dust particle, interparticle distance in a Coulomb cluster and so on. The PIV (Particle Image Velocimetry) system described in the above section to study dynamics of dust particles in a complex plasma is tested first in YCOPEX before we apply to a more complicated cryogenic system. The YCOPEX has a unique feature to confine dust particles two dimensionally at the edge of the sheath on the metallic plate and the collective motion of dust particles can be controlled by tilting the chamber itself (See publication Nakamura and Ishihara (2008) ).

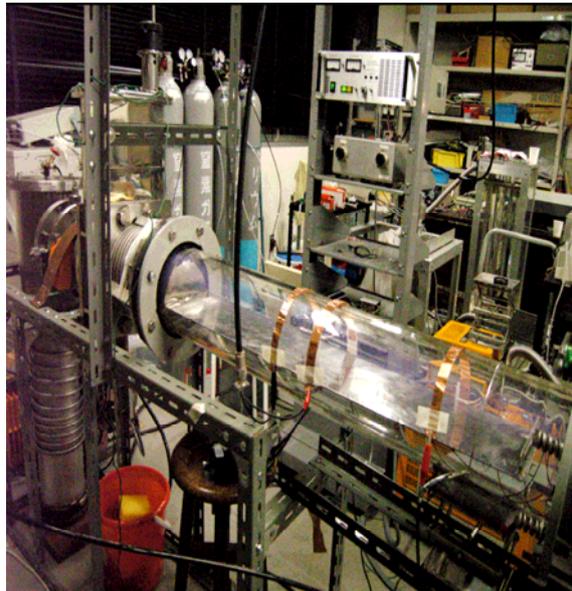


Fig. 10A YCOPEX  
(Yokohama Complex Plasma Experiment).

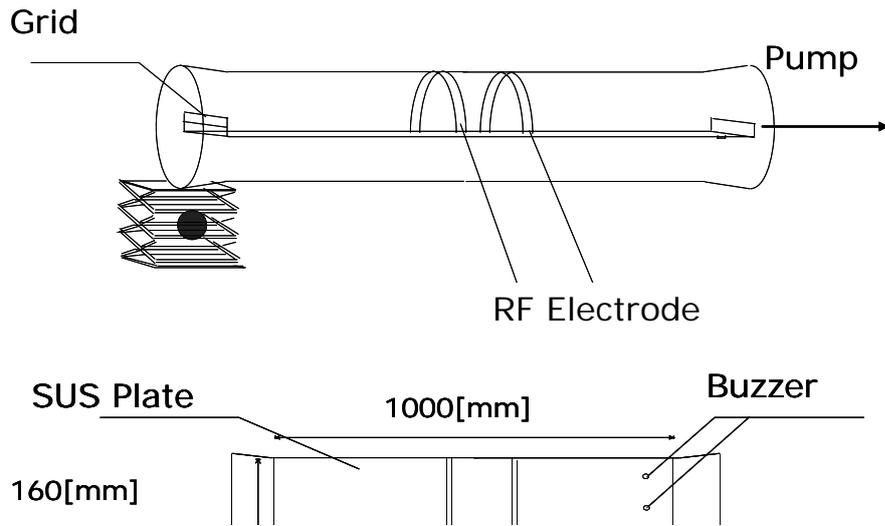


Fig. 10B Schematic of YCOPEX

The jack lifts the left corner of the chamber, producing the parallel to the plate component of gravitational force on dust particles.

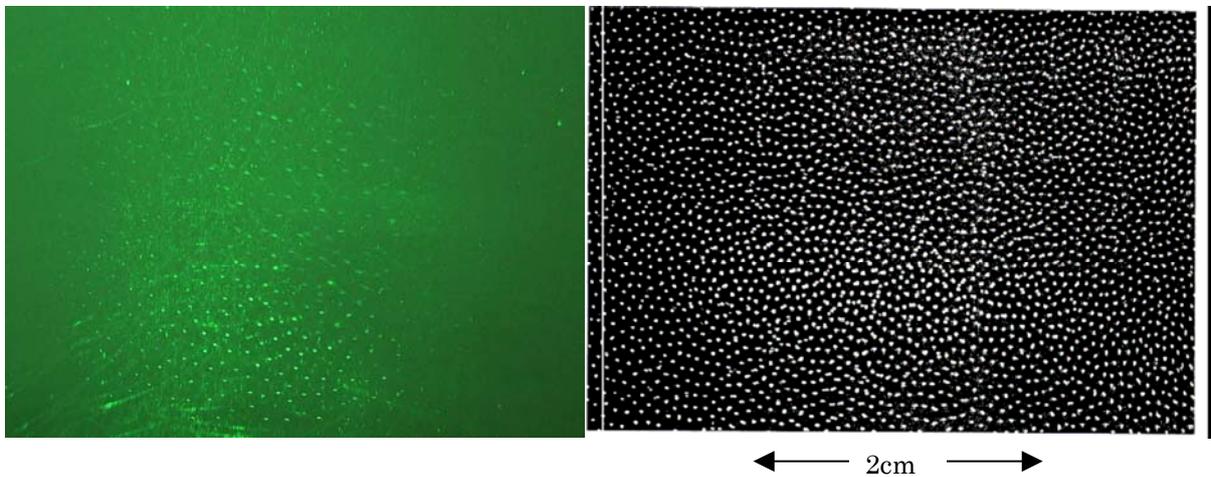


Fig. 11 Dust particles observed in a large area device YCOPEX.

#### 4) Theory/Simulation

Simulation of dust clusters forming in a plasma has been carried out. The CME (configuration of minimum energy) structures have been identified depending on the form of plasma confinement. Novel features of dust structures are reported in the Physics of Plasmas (see Kamimura, Suga and Ishihara, 2008). Two invited talks were given by the principal investigator on this subject, one in *the 9th International Workshop on the Interrelationship between Plasma Experiments in Laboratory and Space* in Australia and the other in *the Summer College on Plasma Physics at Abdus Salam International Centre for Theoretical Physics* in Italy.

Analytical study of dust diffusion in cryogenic plasma was presented by a doctoral student Wataru Sekine at the *9th International Workshop on the Interrelationship between Plasma Experiments in Laboratory and Space* in Australia in August, 2007.

### IV. Publication/Presentation

#### 1. Publications

1. O. Ishihara, Complex Plasma: Dusts in Plasma, *Journal of Physics D: Appl. Phys.* **40**, R121-R147 (2007).  
[According to the publisher this article has been recognized as one of 3% articles accessed over 500 times in the year 2007 across all IOP journals.]
2. T. Kamimura, Y. Suga and O. Ishihara, Configurations of Coulomb Clusters in Plasma, *Physics of Plasmas* **14**, 123706-1 -11(2007) .
3. M. Shindo and O. Ishihara, *Study of Complex Plasmas*, in Nano- and Micromaterials, ed. by K. Ohno, M. Tanaka, J. Takeda, and Y. Kawazoe (Springer Berlin Heidelberg, 2008), Chap. 13 (pp. 313-327).
4. Y. Nakamura and O. Ishihara, A Complex plasma device of large surface area, *Review of Scientific Instruments*, **79**, 033504-1-033504-4 (2008).
5. C. Kojima, J. Kubota, Y. Tashima and O. Ishihara, Dust dynamics in wake channel, *The Japan Society of Microgravity Application*, **25**, 353-356 (2008).
6. O. Ishihara, Complex Plasma Research under Extreme Conditions, in *Multifacets of Dusty Plasmas*, Fifth International Conference on the Physics of Dusty Plasmas (Ponta Delgada, Azores, Portugal, 18-23 May, 2008) edited by J.T. Mendonça, D. P. Resends and P. K. Shukla, pp. 139-142.
7. J. Kubota, C. Kojima, W. Sekine and O. Ishihara, Dust Charge in Cryogenic Environment, *Multifacets of Dusty Plasmas*, Fifth International Conference on the Physics of Dusty Plasmas, (Ponta Delgada, Azores, Portugal, 18-23 May, 2008) edited by J.T. Mendonça, D. P. Resends and P. K. Shukla, pp. 235-236.

## 2. Conference Presentations

1. O. Ishihara and T. Kamimura, Configurations of Coulomb Clusters in Complex Plasma , The 9th International Workshop on the Interrelationship between Plasma Experiments in Laboratory and Space (IPELS) , 5th-10th August 2007, Palm Cove Resort, Cairns, Australia (**Invited talk**).
2. W. Sekine and O. Ishihara, Cold dust cluster in the liquid helium environment, The 9<sup>th</sup> International Workshop on the Interrelationship between Plasma Experiments in Laboratory and Space, 5<sup>th</sup> - 10<sup>th</sup> August 2007, Palm Cove Resort, Cairns, Australia
3. Osamu Ishihara, The Structure Formation of Coulomb Clusters, Summer College on Plasma Physics, Abdus Salam International Centre for Theoretical Physics (ASICTP). August 20 – August 24, 2007, Trieste, Italy (**Invited talk**).
4. C. Kojima, J. Kubota, Y. Tashima and O. Ishihara, Dust dynamics in wake channel, Third International Symposium on Physical Sciences in Space (3<sup>rd</sup> ISPS 2007), Oct. 22 - 26, 2007, Nara, Japan.
5. J. Kubota, C. Kojima, W. Sekine and O. Ishihara, Dust Charge in Cryogenic Environment, Fifth International Conference on Physics of Dusty Plasma (ICDP5) (May 18-21, 2008, Ponta Delgada, Azores, Portugal)
6. O. Ishihara, Complex Plasma Research under Extreme Conditions, Fifth International Conference on Physics of Dusty Plasma (ICDP5) (May 18-21, 2008, Ponta Delgada, Azores, Portugal) (**Invited talk**).
7. J. Kubota, C. Kojima, W. Sekine and O. Ishihara, Observation of dusts structure in cryogenic environment (International Congress on Plasma Physics 2008, September 8-12, 2008, Fukuoka, Japan)
8. Wataru Sekine, Osamu Ishihara and Marlene Rosenberg, Dust dynamics in cryogenic environment (International Congress on Plasma Physics 2008, September 8-12, 2008, Fukuoka, Japan)
9. Masako Shindo, Natsuko Uotani and Osamu Ishihara, Dust charge in collisional plasma in liquid helium vapor (International Congress on Plasma Physics 2008, September 8-12, 2008, Fukuoka, Japan).

## 3. Domestic Conference Abstracts

1. Y. Suga, T. Kamimura and O. Ishihara, Coulomb clusters by dust particles in a plasma, JPS Fall meeting, September 21-24, 2007. Sapporo, Hokkaido University.
2. Y. Fukuda, N. Hosoi, M. Shindo and O. Ishihara, Structure of charged dust particles near liquid helium surface, JPS Fall meeting, September 21-24, 2007. Sapporo, Hokkaido University.
3. W. Sekine and O. Ishihara, Diffusion process of dust particles in a cryogenic plasma environment, Japan Astronomy Society Annual meeting, September 26-28, 2007. Gifu, Gifu University. A0090a.
4. C. Kojima, J. Kubota, O. Ishihara, Observation of moving dust particles in the ion wind, JSPF (Japan Society of Plasma Science and Nuclear Fusion) Annual meeting, November 27-30, 2007, Himeji. 29pB22P
5. K. Mita, C. Kojima, J. Kubota, Y. Tashima and O. Ishihara, "Influence of plasma under cryogenic environment on Coulomb crystal" JSPF (Japan Society of Plasma Science and Nuclear Fusion) Annual meeting, November 27-30, 2007, Himeji. 29pB23P.
6. T. Yamada, Y. Tomita and O. Ishihara, "Absorption of a charged particle to a spherical dust in uniform weak magnetic field," JSPF (Japan Society of Plasma Science and Nuclear Fusion) Annual meeting, November 27-30, 2007, Himeji. 29pB24P
7. Y. Nakamura and O. Ishihara, Measurement of Neutral Drag Force on Microparticles, 8<sup>th</sup> Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Dec. 20-21, 2007). O-6.
8. Yuta Suga, Tetsuo Kamimura, Osamu Ishihara, Helical Structures Formed by Charged Dust Particles, 8<sup>th</sup> Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Dec. 20-21, 2007). P-11.
9. Wataru Sekine and Osamu Ishihara, Diffusion process of dust particle in cryogenic environment, 8<sup>th</sup> Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Dec.

- 20-21, 2007). P-13.
10. C. Kojima, K. Mita, J. Kubota, Y. Tashima, and O. Ishihara, Observation of random motion of charged dust particles in a cryogenic plasma, 8<sup>th</sup> Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Dec., 20-21, 2007). P-14.
  11. J. Kubota, C. Kojima and O. Ishihara Moving dust particles up with damped oscillation in the sheath, 8<sup>th</sup> Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Dec. 20-21, 2007). P-15.
  12. M. Shindo, Y. Fukuda, N. Hosoi and O. Ishihara, Measurement of dust charge attached in a plasma with high gas pressure, 8<sup>th</sup> Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Dec. 20-21, 2007). P-16.
  13. Yuta Suga, Tetsuo Kamimura, Osamu Ishihara, Stable Configurations of Helical in Anisotropic Confinement, Annual Meeting of Physical Society of Japan, (Kinki University, March 22-26, 2008) 24pRE-7
  14. M. Shindo, Y. Fukuda, N. Hosoi, and O. Ishihara, Measurement of electric charge on a dust particle attached in a plasma in liquid helium vapor, Annual Meeting of Physical Society of Japan, (Kinki University, March 22-26, 2008) 24pRE-8
  15. W. Sekine, O. Ishihara, M. Rosenberg, Theoretical study on complex plasma in cryogenic environment Annual Meeting of Physical Society of Japan, (Kinki University, March 22-26, 2008) 24pRE-9
  16. W. Sekine, O. Ishihara, M. Rosenberg, Theoretical study on complex plasma in cryogenic environment Annual Meeting of Physical Society of Japan (Kinki University, March 22-26, 2008)
  17. J. Kubota, C. Kojima, W. Sekine, Y. Nakamura, O. Ishihara, Dust charge in a plasma under cryogenic environment, Fall meeting of Physical Society of Japan, September of 20-23, 2008. Iwate University) 21pZB-10
  18. Wataru Sekine, Osamu Ishihara, Marlene Rosenberg Interaction between dust particles and background plasma Fall meeting of Physical Society of Japan, September of 20-23, 2008. Iwate University) 21pZB-11

#### **4. Doctoral dissertation**

Chikara Kojima, Study of a complex plasma in cryogenic environment (June, 2008)

#### **V. Collaboration**

**Professor Marlene Rosenberg** of University of California, San Diego, USA visited our Lab from March 3 to March 10, 2007. Our collaboration on cryogenic complex plasma started and we have submitted a paper to present at the annual meeting of Physical Society of Japan in March 2008 in Osaka, Japan.

**Professor Oleg Petrov** and Dr. Sergey Antipov of Joint Institute for High Temperatures of the Russian Academy of Sciences (former Institute for High Energy Densities, Russian Academy of Science) , Moscow, Russia visited our lab from December 22 to 23, 2007. We exchanged the detailed information on the experiments of cryogenic complex plasma experiments. We are the only two groups in the world to carry on the cryogenic complex plasma experiments.

## ATTACHMENT

1. Publications
2. International Conference Presentations (power point cover pages)
3. Domestic meeting records