Repeatable Intense Beam Generation of Micro-Particles Attached with 10^7 Electrons

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Intense beams of micro-particles, each attached with approximately 1.1×10^7 electrons, were generated repeatedly. The particle was a spherical divinyl benzene polymer of 10 μm diameter, coated with 450 Å thick gold. More than 5000 charged particles were extracted outside in 0.5 s using an assembly composed of a reservoir, a helicoid conveyer, an oscillating sawtoothed plate and a charging section of a high electric field.

Keywords: highly charged particle, pulsed beam source, particle injector

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1. Introduction

Charged micro-particles present in background plasmas have been studied extensively from the perspective of applications and basic physics. It is well studied that charge on the surface of a micro-particles immersed in plasma depends on the particle's size, shape and plasma parameters [1–4]. Charging of levitating spherical micro-particles with distributed radii has been examined in a DC discharge [5]. Dusty plasmas with strongly asymmetric (rodlike) particles were investigated experimentally and theoretically [6, 7]. Quite recently, it has been extended to the charging of organic cells placed in plasma [8].

Accelerating of highly charged micro-particles was also used to study either effects at their bombardment onto target surfaces [9, 10] or getting more energetic particles with limited acceleration potentials [11, 12]. These experiments principally concern single particle dynamics and do not require large ensembles of particles. On the contrary, for experiment to provide collective phenomena caused by highly charged particles, higher density of particles are required. Highly charged particles are also indispensable to examine effects of surrounding very low electric potential, as we frequently encounter cases of experiments simulating astrophysical phenomena. For confinement experiment in a potential well, pulsed and intensive beams having larger number of particles in a single pulse become necessary, since such beams should be injected into the trap shortly, compared with confinement time.

A method to generate such intense beams of micro-particles is reported here. The beam can be generated in vacuum many times with good reproduction. About 5000 particles, attached with 10^7 electrons for each, are produced in a pulse of 0.5 s.

Micro-particles in this experiment are of spherical divinyl benzene polymer of the density of 1.98 g/cm^3 and the diameter of 10 μm, coated with 450 Å thick gold. Each particle has a mass of 1.3 μg. Metal coating on an insulator surface changes its characteristics of the surface, i.e., electrons are pulled onto the surface by induced image charges and they are grasped on the surface. Using polymer of a low density, we can make light micro-particles having metallic surface characteristics instead of the use of whole metal particles.

2. Apparatus

The beam source consists of a reservoir of particles, a helicoid conveyer, i.e., so-called screw conveyer, and a section of charging and acceleration as shown in Fig. 1.

The helicoid conveyer is a stainless spiral of 2.2 mm diameter and 2.0 mm pitch, which is enclosed in a stainless tube. It sends the particles onto a sawtoothed plate. The number of particles supplied by one rotation of the conveyer is 1310±50, which has been determined from

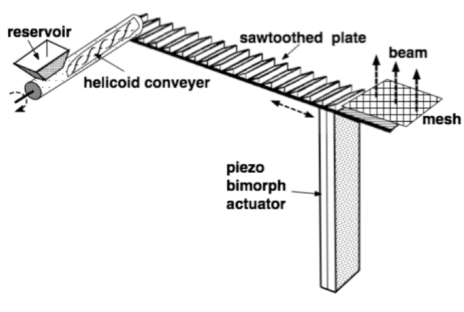

Fig. 1 Illustration of the beam source of highly charged micro-particles.

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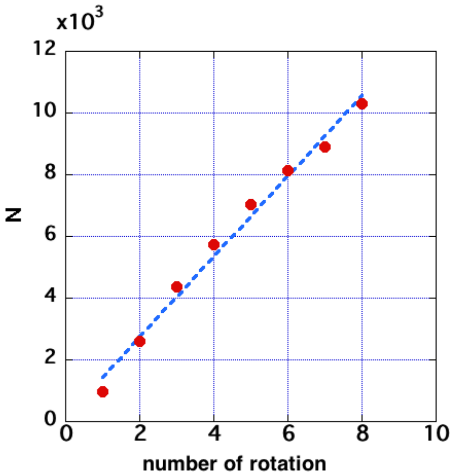

Fig. 2 Conveyed particle number N as a function of the conveyer. Dotted line is the fitting one to the observed plots.

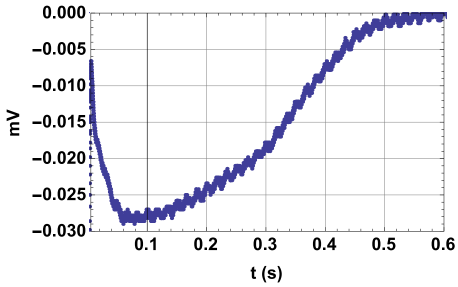

Fig. 3 Faraday cup signal for the case of 6550 particles (6 rotations of the conveyer) at 1 MΩ input impedance.

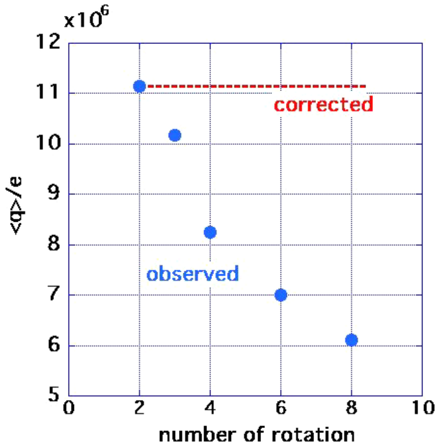

Fig. 4 Particle charge $\langle q \rangle$ determined from observed Faraday cup signals.

the total weight of particles considering the mass of single particle of 1.3 µg. Figure 2 shows the conveyed particle number N as a function of the rotation number of the conveyer. An iron block surface of 2 cm width is formed to a sawtoothed shape by using a wire-cut electrical discharge machine. Its pitch and height are 0.4 mm and 0.2 mm, respectively. Making this block a formwork, a 10 µm thick silver foil is compressed on the surface to mold it to the sawtoothed shape. The foil is adhered to a 0.1 mm thick brass plate fixed with a piezo-bimorph actuator, which oscillates the sawtoothed foil perpendicularly to its grooves at 157 Hz and then pushes the particles towards a flat portion made at the end of the foil. Oscillating sawtoothed surface gives different directional momenta on particles according to direction of oscillation and produces directional motions of the particles. The flat portion works as a pileup space for the conveyed particles.

A grounded perforated copper foil of 100 mesh is set 2 mm apart to the flat portion. When a pulse V is applied on the plate, the resultant E field affects the conveyed particles. High electric field on the surface of each particle is produced because of its small radius and then causes a contact-charging on it [13]. In this experiment, $V = -1100$ V is always applied during the extraction.

Thus, the extracted charged particles are collected with the Faraday cup that is 50 mm in diameter and set 8.6 mm from the grid mesh. The gap between the Faraday cup and the mesh cannot be ignored when the extracted particles become large in number. The source assembly is set in a vacuum vessel of pressure of about 10^{-3} Pa.

3. Experimental Results

Figure 3 shows the signal of the Faraday cup with time. The signal continues for 0.5 s. The extraction is completed within 0.5 s and, after then, no particle rests on the flat portion. The total charge of extracted particles Q is determined by integrating the Faraday cup current signal i_F with time. Since the particle number N is known, we can find the effective charge of each particle $\langle q \rangle$ as

$$Q = \int i_F \mathrm{d}t = N \langle q \rangle \,.$$

Figure 4 indicates the result, where e is the elemental charge. However, particles leak from the gap between the mesh and the Faraday cup, which is noticed by photograph and also naked eye through a vacuum window. Extracted particles attached with large electrons produce the spatial electric field that forces the particles to escape through the gap. As is shown in Fig. 4, this leakage is nearly proportional to N. The dotted line in Fig. 4 are corrected ones since the leak becomes negligibly small at $N \sim 2.6 \times 10^3$ as noted. The particle charge are then about $\langle q \rangle = 1.1 \times 10^7\, e$.

4. Conclusive Remarks

An intense pulsed beam source of highly charged micro-particles has been developed. The beam can be generated repeatedly in an enclosed vacuum vessel. The beam particle number in a pulse can be adjusted by rotation of the helicoid. The reported source is a fundamental one and can be modified according to experimental purposes. Deceleration or acceleration of the beam energy can be attained by placing an electrode in front of the mesh.

This beam source would be applied for confinement experiments of non-neutral plasmas where electric potential barriers are very weak. Simulating experiments on planets and relating phenomena would also be considered as candidates.

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[1] L. Boufendi, M.Ch. Jouanny, E. Kovacevie, J. Berndt and M. Milikian, J. Phys. D **44**, 1 (2011).
[2] J.E. Allen, Phys. Scr. **45**, 497 (1992).
[3] S.M. Collins, D.A. Brown, J.F. O'Hanlon and R.N. Carlile, J. Vac. Sci. Technol. A **14**, 634 (1996).
[4] S.A. Khrapak, S.V. Ratynskaia, A.V. Zobnin, A.D. Usachev, V.V. Yaroshenko, M.H. Thoma, M. Kretschmer, H. Hofner, G.E. Morfill, O.F. Petrov and V.E. Fortov, Phys. Rev. E **72**, 016406 (2005).
[5] S. Nunomura, N. Ohno and S. Takamura, Jpn. J. Appl. Phys. **36**, L949 (1997).
[6] A.V. Ivlev, A.G. Khrapak, S.A. Khrapak, B.M. Annaratone, G. Morfill and K. Yoshino, Phys. Rev. E **68**, 026403 (2003).
[7] B.M. Annaratone, A.G. Khrapak, A.V. Ivlev, G. Söllner, P. Bryant, R. Sütterlin, U. Konopka, K. Yoshino, M. Zuzic, H.M. Thomas and G.E. Morfill, Phys. Rev. E **63**, 036406 (2001).
[8] A. Sanpei, T. Kigami, H. Kanaya, Y. Hayashi and M. Sampei, IEEE Trans. Plasma Sci. **46**, 718 (2018).
[9] Y. Enokido, R. Ishigami, M. Kondo, J. Goto, K. Sekine and F. Fukuzawa, J. Nucl. Sci. Technol. **37**, 750 (2000).
[10] F. Fukuzawa, Oyo Butsuri **60**, 720 (1991) [in Japanese].
[11] H. Shelton, C.D. Hendricks Jr. and R.F. Wuerker, J. Appl. Phys. **31**, 1243 (1960).
[12] J.F. Friichtenicht, Rev. Sci. Instrum. **33**, 209 (1962).
[13] N. Ikawa, Y. Mori and T. Ide, Seimitu Kikai **43**, 91 (1977) [in Japanese].