

HYPERVELOCITY DUST STORM LAUNCHED WITH A COAXIAL PLASMA GUN*

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Abstract

A dust storm consisting of carbon grains accelerated to speeds up to ~3 km/s has been launched by a plasma jet produced in a coaxial gun. Diamond and graphite powders with grain radii of 0.5 to 30 microns have been used. A distinctive feature of this plasma accelerator is that it can use different types of gases and can operate with microparticles having any shape and a large range of sizes. Deuterium gas and carbon dust is chosen to be compatible with fusion plasmas as a diagnostic tool. The operating voltages of the coaxial gun are between 5 and 10 kV and the maximum measured discharge current is ~250 kA. Imaging of the plasma jet exiting the gun with speeds of 25 to 60 km/s and accelerated by the $\mathbf{J} \times \mathbf{B}$ force shows a good collimation of the flow for about 1.5 m, before it diffuses into a large vacuum tank.

accelerate several microparticles simultaneously, regardless of their shape or size. The plasma flow can exert sufficient drag force even on grains with a radius of a hundred microns, and impart accelerations as large as $a_d=500g$ ($g=9.81 \text{ m/s}^2$) [10-11]. The acceleration process is usually accompanied by intense heating of the grains due to the dense plasma particle fluxes colliding with the grains. As a result the dust surface can reach high temperatures and emit visible radiation. Thus, the accelerated grains glow by themselves, a feature that is very useful for imaging dust in-situ with a high speed video-camera. Partial vaporization of dust can become significant especially for grains no larger than a few microns [12]. In this paper we report on the simultaneous acceleration of a few hundred dust grains to speeds up to 3 km/s by plasma jets.

I. INTRODUCTION

Coaxial plasma guns [1] have been extensively investigated since the 80's as a possible pathway to obtaining fusion energy [2-3]. The potential of cold and dense plasma flows formed in coaxial guns to accelerate pellets to high velocities which could be used for meteorite impact studies has been early recognized and utilized [4]. Later, new applications for coaxial guns emerged such as tokamak refueling [5], surface processing with plasma flows [6], or dust acceleration and injection in fusion plasmas for diagnostic purposes [7]. The main feature of a coaxial gun is its capability to produce and eject plasma at speeds of the order of 10-100 km/s. Gas introduced between a center rod and a coaxial cylinder is ionized and swept away along the gun axis by the electromagnetic force which is proportional with the current density on the electrodes and its self-generated magnetic field [1]. A microparticle accelerator based on a coaxial plasma gun [8] has multiple advantages: it has a compact size and operates with voltages of a few kV compared to electrostatic accelerators which occupy large volumes and require MV, it can use different gases although the plasma flow speed may vary, depending on the ions mass [9], and it can

II. EXPERIMENT

A. *Plasmadynamic Dust Accelerator*

The plasmadynamic dust accelerator built at Los Alamos

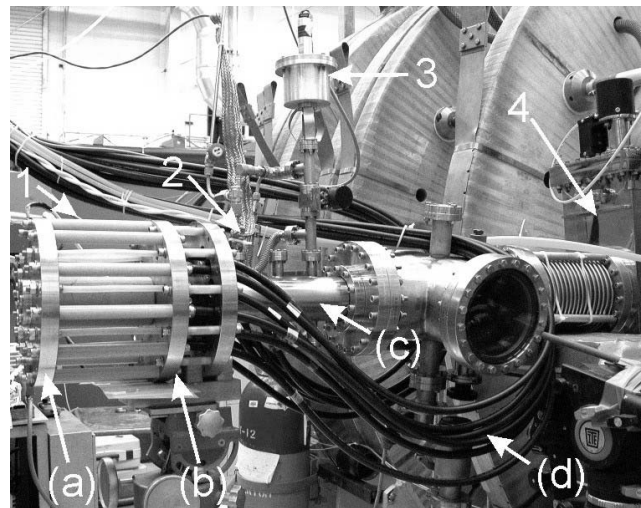


Figure 1. Plasmadynamic accelerator: coaxial plasma gun (1), gas puff valve (2), dust dispenser (3), and isolation valve (4). The coaxial gun includes a center electrode and a grounded outer electrode attached to stainless steel

* Work supported by DOE LANS, Contract No. DE-AC52-06NA25396, through The Office of Science

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Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE JUN 2007		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Hypervelocity Dust Storm Launched With A Coaxial Plasma Gun				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Los Alamos National Laboratory, Plasma Physics Group P-24, Los Alamos, NM 87545				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.					
14. ABSTRACT A dust storm consisting of carbon grains accelerated to speeds up to ~3 km/s has been launched by a plasma jet produced in a coaxial gun. Diamond and graphite powders with grain radii of 0.5 to 30 microns have been used. A distinctive feature of this plasma accelerator is that it can use different types of gases and can operate with microparticles having any shape and a large range of sizes. Deuterium gas and carbon dust is chosen to be compatible with fusion plasmas as a diagnostic tool. The operating voltages of the coaxial gun are between 5 and 10 kV and the maximum measured discharge current is ~250 kA. Imaging of the plasma jet exiting the gun with speeds of 25 to 60 km/s and accelerated by the $J \times B$ force shows a good collimation of the flow for about 1.5 m, before it diffuses into a large a vacuum tank.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 4	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

plates (a) and (b) respectively, an acceleration channel (c) and power cables (d).

is shown in Fig.1 [13]. The design of the coaxial gun is similar to models that have been previously described in the literature [4, 8]. The gun electrodes are shown in Fig. 2. A center rod with a diameter of 1.9 cm and a coaxial cylinder with an inner diameter of 3.1 cm are separated by an insulating ring made of G-10. The inter-electrode gap is 21 cm long.

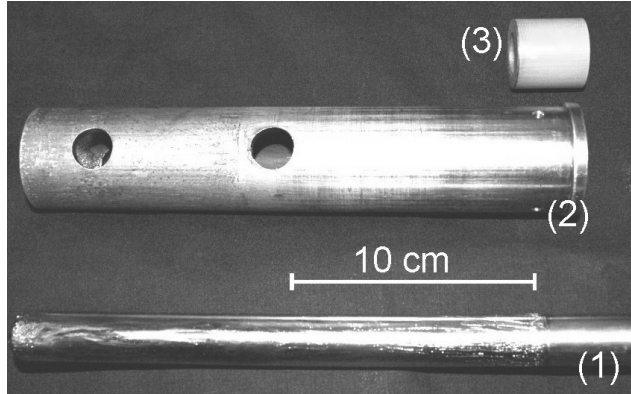


Figure 2. Center electrode (1), coaxial electrode (2) and insulating ring (3).

About 15-20 TorrL of gas is puffed with a fast-valve from a plenum with 176 cm³ through the middle hole of the coaxial electrode. The plenum is pre-filled before each shot with deuterium at pressures between 8 and 13 atm. The plasma is fired 1 ms after opening of the puff valve. More details about the construction of the plasmadynamic accelerator can be found in Ref. [13].

A discharge is ignited by closing the circuit between the gun and a capacitor bank with 1 mF which stores a maximum of 50 kJ for charging voltages between 5 and 10 kV. Fig. 3 shows an image of the ejected plasma flow as it enters a large vacuum tank with 1.5 m diameter, through a side port situated 0.85 m downstream the gun muzzle. The picture is recorded by a high-speed camera (DICAM PRO, the Cooke Corporation) using a fish eye lens with 16 mm f/4. The exposure is set at 50 ns. The well collimated plasma flow presented in Fig. 3 is recorded at 57 μ s from t=0 of the discharge. Note the bright central filament in the flow, with a diameter of about 1-1.5 cm. The flow eventually dissipates at about 2 m distance from the gun exit.

The plasma flow speed is measured from the signals of two photodiodes placed 0.9 m apart, which have perpendicular view on the flow. The time delay between the peaks in the signals Ipd1 and Ipd2 shown in Fig. 4 (a) is 26 μ s, and therefore a plasma flow speed $v_f=34$ km/s is deduced. The shot duration is ~350-400 μ s as observed in the signal Ipd3 of a third photodiode which acquires the light emitted from within the coaxial gap, Fig. 4 (b). The visible plasma plume which expands in the large vacuum tank on a direction transversal to the flow is a measure of the ion thermal speed. A simple measurement of the

expansion angle in Fig. 3 provides an estimate for the ion temperature $T_i \approx 1.8$ eV.

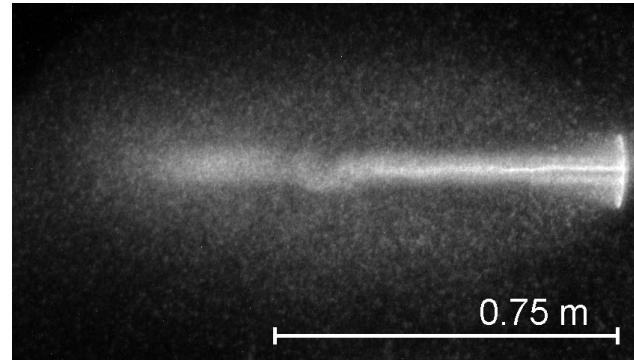


Figure 3. Plasma flow entering a large vacuum tank: exposure is set at 50 ns and the delay is 57 μ s.

The capacitor bank is charged at 8 kV for the shot presented in Figs. 3 and 4. Once the discharge is initiated, the voltage between the electrodes drops to 1.3 kV in about 5 μ s, Fig. 4 (c). An ionization front starts propagating within the gas filling the coaxial gap, leading to a current build up to a maximum of 210 kA after 40 μ s, Fig. 4(d). The variation in time of both instantaneous voltage and current are characteristic for an over-damped oscillatory circuit, with a slight phase delay between the two curves.

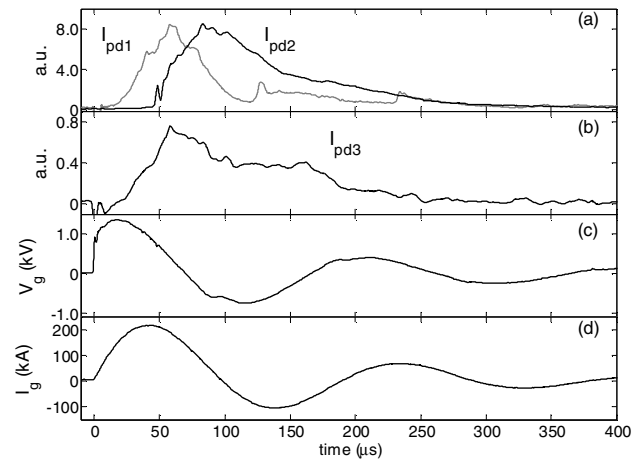


Figure 4. An 8 kV shot: (a) photodiode signals of the plasma light emission at 0.25 m (Ipd1) and at 1.15 m (Ipd2) from the gun muzzle, (b) light emission from within the coaxial gap, (c) voltage between electrodes and (d) discharge current.

B. Detection of Hypervelocity Dust

A dust dispenser under vacuum, mounted at the top of the accelerator barrel is shaken continuously for 2-3 seconds, during which a plasma shot is fired. The dust grains are free falling from about 0.5 m in front of the gun muzzle. The fast moving plasma flow formed in a period of a few microseconds will intersect the dust “rain” and drag along the grains caught in its path. Momentum is imparted to the

dust grains by the plasma particle fluxes bombarding their surface. The kinetic energy of the ions and electrons deposited on the grain surface heat the dust grains to temperatures sufficiently high to cause them self-glow. An image of multiple grains glowing like tracers and flying in the direction of the flow is presented in Fig. 5(a). The image was taken 400 μ s after firing the gun and has an exposure of 4 μ s. The speed of dust showed in this image, calculated from the length of glowing grains traces, is in between 0.5 km/s and 2.2 km/s. The camera was oriented almost perpendicular ($\sim 76^\circ$) on the dust trajectories, and installed about 2 m away. It used a telephoto lens with 500 mm f/4 to magnify a region of about 12 by 14 cm, situated at 1.6 m downstream the gun muzzle. Fig. 5 (a) shows only a section which contains about 90 grains of the whole recorded picture.

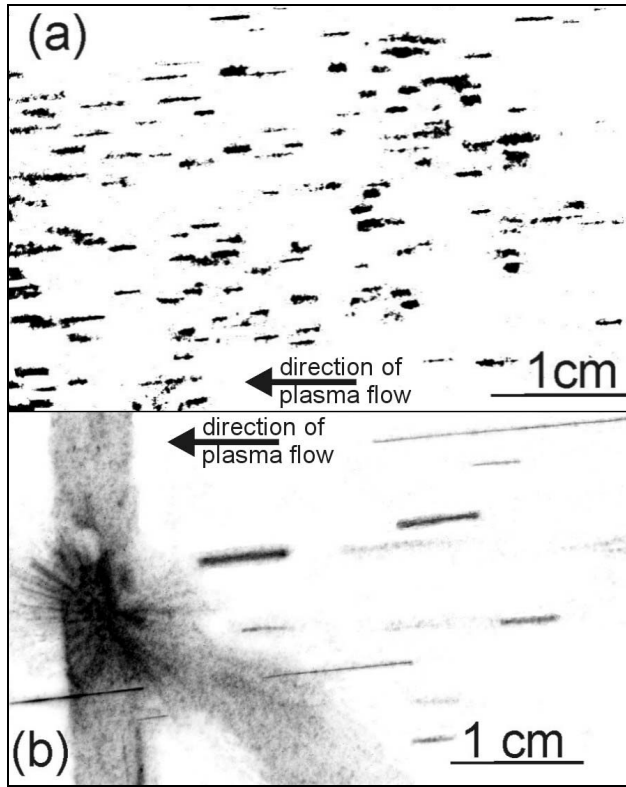


Figure 5. Color inverted pictures of hypervelocity dust flying in the direction of the plasma flow. The exposure is set at 4 μ s in (a), and 12 μ s in (b). Both images were taken at $\sim 1.6 \pm 0.05$ m downstream the gun muzzle.

An image showing the collision of a grain with a stainless steel plate can give a more intuitive proof of the high speed of dust. In Fig. 5(b) the grain made of soft graphite shatters into a shower of small pieces due to the impact force which is proportional with the grain's momentum. Several bright traces can be seen originating at the point of impact and uniformly distributed in a 2° angle, which seem to be the trajectories of flying debris resulted from the violent impact. From the exposure time which is set to 12 μ s and the length of the observed radial trajectories, a

lower limit for the speed of these flying dust remnants can be calculated: ~ 300 -800 m/s. The traces of other moving grains are seen near the plate, with lengths varying between 0.7 cm and 3.7 cm, which correspond to a range of dust speeds between 0.5 and 3.1 km/s.

The dust speed can be also obtained as an average over several stages of dust motion, from the moment it is dropped in front of the gun muzzle until the moment it is imaged by the camera, as shown in Fig 6. In the first stage dust is dragged by the puffed gas flowing out of the coaxial gap. After 1ms the plasma is fired and the grains continue their motion, this time dragged by the plasma flow. Once the plasma dissipates the grains maintain their trajectories with the speed achieved during plasma acceleration. The speed of grains shown in the histograms is thus calculated considering the total time of flight during the length of their trajectories between the launch and detection positions, which is 1.6 m. The obtained values agree well with those measured from glowing dust traces such as those presented in Fig. 5. Occasionally however, grains with higher speed can be observed, as in Fig. 5(b).

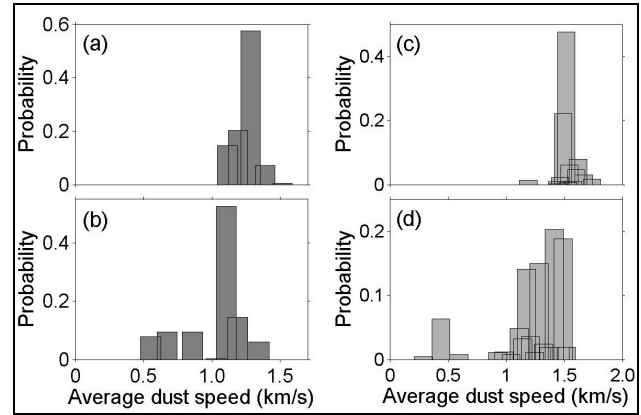


Figure 6. Average speed of diamond grains for 10 kV shots in (a) and 8 kV shots in (b). Average speed of graphite grains for 8 kV shots in (c) and 6 kV shots in (d).

While the plasma drag force is proportional with the dust radius and the density of charged particles colliding with the grain, the simultaneous observation of fast and slower grains can only be an indication of density non-uniformity in the plasma flow cross-section. This argument is supported by observations of bright filaments, like the one shown in Fig. 3, which possibly indicate higher plasma density in some limited regions of the plasma flow.

The drag exerted by the neutral gas flowing with the thermal speed before pressure equilibration in the system found at $\sim 3 \times 10^{-6}$ torr can be written as [14]:

$$F_n = \frac{8}{3} \sqrt{2\pi} r_d^2 P_n \xi, \quad (1)$$

where r_d is the grain radius, P_n is the pressure of the neutral gas, and $\xi \approx 1.4$ is a factor that accounts for diffuse reflection of neutrals on the grain surface. For deuterium gas with $P_n = 10$ torr at room temperature the

acceleration of dust grains can reach very high values $a_{\text{dn}} \approx 10^4\text{-}10^6 \text{ m/s}^2$ for about $\sim 0.8 \text{ ms}$. The drag exerted by the plasma flow as a result of direct impact of ions with a grain can be written as [14]:

$$F_p = \frac{16}{3} \sqrt{\pi} r_d^2 k_B T_i n_i w \sqrt{1 + \frac{9\pi}{64} w^2}, \quad (2)$$

where k_B is the Boltzmann constant, T_i is the ion temperature, n_i is the plasma density and $w = (v_p - v_d)/v_{Ti}$ is the grain speed v_d relative to the plasma flow speed v_p , normalized by the ion thermal speed $v_{Ti} = (2k_B T_i/m_i)^{1/2}$ [11-12,15]. Electron drag is neglected here due to small electron mass. Also the contribution of long range Coulomb interactions between streaming ions and dust grains is neglected. This approximation is justified by the small plasma screening length $\lambda_D \sim 10^{-7} \text{ m}$ compared with the grain radii, for the parameters of the plasma flow presented here: $T_{e(i)} \sim 2 \text{ eV}$ and density $n_{e(i)} \sim 2 \times 10^{22} \text{ m}^{-3}$. Dust acceleration due to plasma drag for $w \approx 3.4$ (in our case $v_p \approx 34 \text{ km/s} \gg v_d \approx 1\text{-}3 \text{ km/s}$) is at least one order of magnitude higher than simple neutral gas drag: $a_{\text{up}} \approx 10^6\text{-}10^8 \text{ m/s}^2$.

Note that the force given in Eq (2) does not depend on the grain charge. Charging of grains present in plasma is inherent. When electron emission at the grain surface is negligible, the equilibrium charge on a grain is negative and gives rise to a potential around the grain which can increase the collection surface b_c^2 for incident ions, beyond the cross section of the grain r_d^2 [14]. In the case of plasma flow with $v_p \gg v_{Ti}$, the symmetry of the potential around the grain is not radial, but strongly deformed in the direction of the flow [15]. In this limit b_c can be approximated with r_d .

III. SUMMARY

Dust grains released in the path of the plasma flow ejected from a coaxial gun are accelerated to speeds up to 3 km/s by the plasma drag force. The grains are made of graphite and diamond and have radii between 0.5 and $30 \mu\text{m}$. The plasmadynamic dust accelerator operates in deuterium at voltages up to 10 kV and has discharge currents of $100\text{-}250 \text{ kA}$. A high speed camera is used to image the flying hypervelocity dust which due to plasma heating is self-illuminated. Applications of hypervelocity dust range from studies of micro-meteorite impacts to diagnosis of fusion plasma or systematic studies of dust interaction with hot plasmas.

IV. REFERENCES

[1] J. Marshall, "Performance of a hydromagnetic plasma gun," *Phys. Fluids*, vol. 3, pp. 134-135, Jan.-Feb. 1960.
[2] C. W. Barnes, T. R. Jarboe, G. J. Marklin, S. O. Knox, I. Henins, "The impedance and energy efficiency of a coaxial magnetized plasma source used for spheromak formation and sustainment," *Phys. Fluids B* vol. 2, pp. 1871-1888, Aug. 1990.

[3] P. M. Bellan, *Spheromaks, A Practical Application of Magnetohydrodynamic Dynamos and Plasma Self-Organization*, Imperial College Press, 2000.
[4] E. B. Igenbergs, E. L. Shriver, and D. W. Jex, "Magnetogasdynamic compression of a coaxial plasma accelerator flow for micrometeoroid simulation," *J. Appl. Phys.*, vol. 44, p. 2177-2187, May 1973.
[5] P. B. Parks, "Refueling of tokamaks by injection of compact toroids," *Phys. Rev. Lett.* vol. 61, pp 1364-1367, Sept. 1988.
[6] K. F. Schoenberg, R. A. Gerwin, R. W. Moses, Jr., J. T. Scheuer, H. P. Wagner, "Magnetohydrodynamic flow physics of magnetically nozzled plasma accelerators with applications to advanced manufacturing," *Phys. Plasmas* vol. 5, pp 2090-2104, May 1998.
[7] Z. Wang, G. A. Wurden, "Hypervelocity dust beam injection for internal magnetic field mapping, ", *Rev. Sci. Instr.*, vol. 74, pp. 1887-1891, Mar. 2003.
[8] A. Hudephol, M. Rott, E. Igenbergs, "Coaxial Plasma Accelerator with Compressor Coil and Radial Gas Injection," *IEEE Trans. Magnetics*, vol. 25, pp 232-237, Jan. 1989
[9] I. P. Dojčinović, M. M. Kuraica, B. M. Obradović, N. Cvetanović, and J. Purić, "Optimization of plasma flow parameters of the magnetoplasma compressor," *Plasma Sources Sci. Technol.*, vol. 16, pp 72-79, Nov. 2006.
[10] Z. Wang, CM Ticos, G.A. Wurden, "Microparticle probes for laboratory plasmas", *IEEE Trans Plasma Sci.*, vol. 34, pp. 242-248, Apr. 2006.
[11] Z. Wang, CM Ticos, G.A. Wurden, "Dust trajectories and diagnostic applications beyond strongly-coupled dusty plasmas", submitted for publication.
[12] C.M. Ticos, Z. Wang, G.L. Delzanno, G. Lapenta, "Plasma dragged microparticles as a method to measure plasma flows", *Phys. Plasmas* vol. 13, pp. 103501, Oct. 2006.
[13] C. M. Ticos, Z. Wang, L. A. Dorf, G. A. Wurden, "Plasmadynamic hypervelocity dust injector for the National Spherical Torus Experiment", *Rev. Sci. Instrum.*, vol. 77, pp 10E304, Sept. 2006.
[14] P.K. Shukla, A.A. Mamun, *Introduction to Dusty Plasma Physics*, Bristol and Philadelphia, IOP, 2002.
[15] I. Hutchinson, "Ion collection by a sphere in a flowing plasma: 3. Floating potential and drag force", *Plasma Phys. Control. Fusion*, vol. 47, pp 71-87, Dec. 2004.