REVIEW OF SCIENTIFIC INSTRUMENTS **77**, 10E304 (2006)

Plasmadynamic hypervelocity dust injector for the National Spherical Torus Experiment

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(Received 5 May 2006; presented on 8 May 2006; accepted 24 May 2006; published online 21 September 2006)

The design and construction of a plasmadynamic device to accelerate dust to hypervelocities is presented. High speed dust will be used to measure magnetic field lines in the National Spherical Torus Experiment. The plasma gun produces a high density ($n_e \approx 10^{18}$ cm^{-3}) and low temperature (a few eV) deuterium plasma, ejected by $\mathbf{J}\times\mathbf{B}$ forces which provide drag on the dust particles in its path. The dust will be entrained by the plasma to velocities of 1–30 km/s, depending on the dust mass. Carbon dust particles will be used, with diameters from 1 to 50 μm. The key components of the plasmadynamic accelerator are a coaxial plasma gun operated at 10 kV (with an estimated discharge current of 200 kA), a dust dispenser activated by a piezoelectric transducer, and power and remote-control systems. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2219384]

I. INTRODUCTION

The confinement and stability properties of plasmas produced in a spherical torus are critically dependent on the configuration of the magnetic field. Diagnosis of the internal magnetic fields is difficult in high temperature plasmas. Established diagnostic techniques are based on the motional Stark effect in injected neutral atoms,[1,2] on the Zeeman splitting in the light emitted by lithium pellets,[3] or on the Faraday rotation of the polarization plane of an incident laser beam.[4] Motional Stark effect (MSE) is especially difficult at low magnetic field [as is the case for the National Spherical Torus Experiment (NSTX)], and it requires an active neutral beam. In contrast, macroscopic pellets are highly perturbative and restricted in time, while polarimetry provides chord averaged values that must be unfolded with density profiles. Physical objects inserted inside plasmas (such as the transient internal probe[5]) have a short lifetime before they vaporize, due to the intense heating by the plasma particles, and therefore their use is also limited.

In our proposed diagnostic,[6–8] determination of the magnetic field line pitch angle will be achieved by monitoring light emission in the ablation plumes of the injected high speed dust with high resolution cameras[9] (one or more spatial views for stereo measurements). The concept of microparticle acceleration to high velocities is well known and has been previously introduced for studying the properties of meteorite impacts. Among different types of microparticle acceleration such as electrostatic,[10] electrothermal,[11] or by compressed gas,[12] we have chosen plasma-based acceleration[13,14] of dust grains with a wide range of sizes, from 1 to 50 μm. The plasma created in a coaxial plasma gun is ejected at several tens of km/s and is expected to have a temperature of only a few eV and density $\approx 10^{18}$ cm^{-3}. In this article we focus on the design and construction of the plasmadynamic accelerator and dust dispenser, which are the main parts of the hypervelocity dust injector (HDI) sketched in Fig. 1(a).

II. THE PLASMADYNAMIC ACCELERATOR

A. Coaxial plasma gun

Acceleration of dust grains is achieved inside a plasmadynamic accelerator which is basically a coaxial plasma gun operated at low pressure in deuterium, whose design is shown in Fig. 1(b). The central electrode has a diameter of 6.4 mm and a length of 229 mm, while the coaxial electrode is a cylinder with a wall thickness of 6.4 mm and inside diameter of 32 mm. The central electrode is welded to a rod with a diameter of 19 mm, which is fixed to a robust metallic disc with a diameter of 253 mm and a thickness of 25 mm, through a 2.75 in. conflat (CF) flange. The disc is provided with 12 holes, where the conducting core of the coaxial power cables are mounted. The coaxial electrode is also mounted on a robust metallic disc with the same diameter and thickness, through a rotatable 2.75 in. CF flange. This disc has 12 holes in which short copper tubes are inserted. The braids of the coaxial power cables are tightened to the copper tubes, while the metallic core of each cable, including the dielectric insulator, passes through and reach for the disc supporting the central electrode. Both discs were initially commercially available zero-length reducers, but they were modified to satisfy our design requirements. Each of them has 24 small holes, drilled near the edge. The two discs are aligned and held together by 12 identical G-10 rods with a length of 152 mm and a diameter of 13 mm, which are screwed on these holes. An alumina cylinder with a thickness of 11 mm surrounds the rod holding the central electrode, reaching inside the two discs. Two O-rings are tightened on the alumina tube and placed on each disc, inside dedicated

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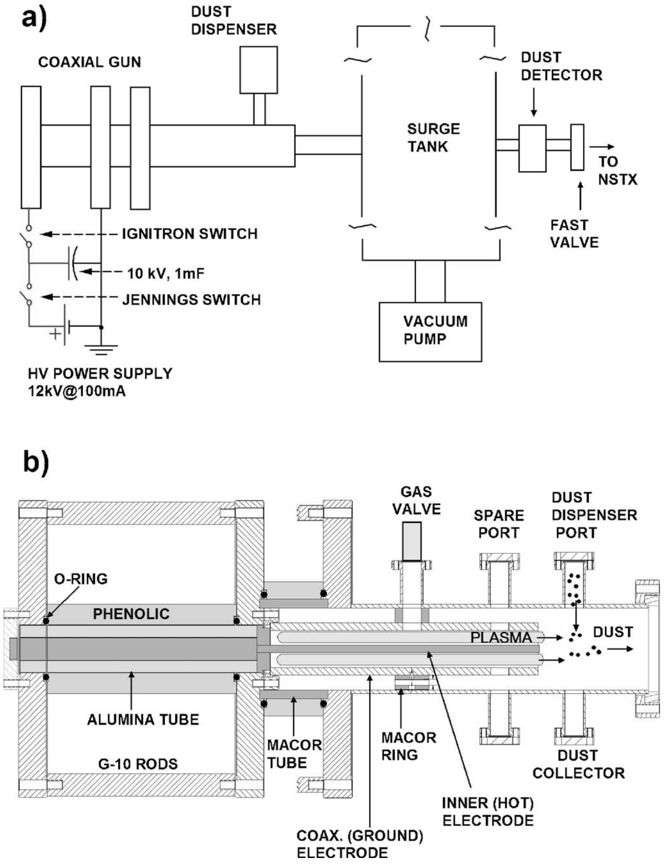

FIG. 1. (a) Schematics of HDI and (b) coaxial gun design.

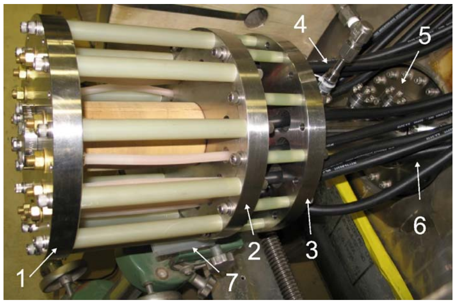

FIG. 2. (Color online) Top view of the coaxial plasma gun. The parts shown are hot electrode (1), grounded electrode (2), gun body (3), gas puff valve (4), dust port (5), power cables (6), and G-10 support (7).

grooves. The vacuum is sealed at the joints of the alumina cylinder with the metallic discs by pressing an outer phenolic cylinder on the O-rings. The electrodes of the gun are inserted in a metallic cylinder, which constitutes the gun body, with an inner diameter of 70 mm and length of 243 mm, welded to a third disc at one end and provided with a 4-5/8 in. CF flange at the other end for mounting purposes. The gun body has five vertical ports provided with 1-1/3 in. CF flanges. Three ports found at the top of the gun body are almost equally spaced. Holes are drilled in the coaxial electrode, at the position of the upper ports. On the first port the gas puff valve is mounted. A macor ring provided with a hole and mounted between the coaxial electrode and the gun body serves as a guiding pipe for the puffed gas. The dust dispenser is mounted on one of the other two upper ports. The lower two ports serve as collectors for the dust sprinkled in excess. The metallic parts of the coaxial gun are made of stainless steel. For initial testing the gun body has been mounted horizontally on a large vacuum tank and rests on a G-10 support screwed to a tripod with adjustable height. The coaxial gun is pictured in Fig. 2.

B. Power system and controls

Two identical capacitors each having 0.5 mF are connected in parallel to massive aluminum plates, on which the 12 coaxial power cables are screwed. The capacitor bank is charged at 10 kV by a Glassman high voltage (HV) source and is discharged through the puffed gas between the coaxial electrodes in a few tens of microseconds. The expected discharge current is $\approx$200 kA. The discharge is triggered by an ignitron model IG5F2, which closes the circuit when it receives an optical pulse of 5 μs duration from a pulse generator. A voltage divider coupled to the electrodes measures the instantaneous voltage between the electrodes during the discharge, while a Rogowski coil mounted around the high voltage end of the ignitron is used to infer the instantaneous current.

The overall system control is maintained by real-time LABVIEW running on field point modules which send digital signals to the relays or to the HV power supply. Analog inputs are available for monitoring the discharge voltage or current in the circuit. The fire sequence follows a routine of a few steps, during which several relays are switched either by applying a 24 V dc voltage or by activating compressed-air contacts. The charging/dumping state of the capacitor bank is set by two 110 V Jennings relays. The electrical circuit has several built-in interlocks for safety reasons, mounted at the access point to the experiment, which disengage the HV and terminate the charging cycle. The capacitor bank is deenergized when not in use by keeping it in contact with soft and hard dumps.

C. Dust dispenser

Dust grains are supplied by shaking a dust container with a piezolectric transducer, as shown in Fig. 3. At the end of their falling trajectories, the grains will be positioned inside the coaxial gun and will constitute the projectiles accelerated by the expanding plasma. The descending time of dust grains through the coaxial gun gap (a few milliseconds) is much longer than the propagation time of the expanding plasma (tens of microseconds) and therefore the dust grains seem stationary for the fast moving plasma. The dust dispenser is a cylindrical box sealed at the top by a removable round plate pressed on an O-ring and is attached at the lower end to a flexible bellows, which is mounted vertically on the port of the gun body. A cup filled with dust and provided with a 1 mm diameter hole at the bottom covered with a fine mesh, is mounted inside the cylinder on four poles. A 300 W Langevin-type transducer is mounted tightly at the top of the box. The transducer is powered by a 150 W ultrasonic generator (Honda Electronics SONAC) oscillating at 28 kHz, which has remote-control capabilities. The number of falling carbon grains is between $\approx$10 and a few thousands, depending on the shaking time which can be varied from 0.1 to 5 s.

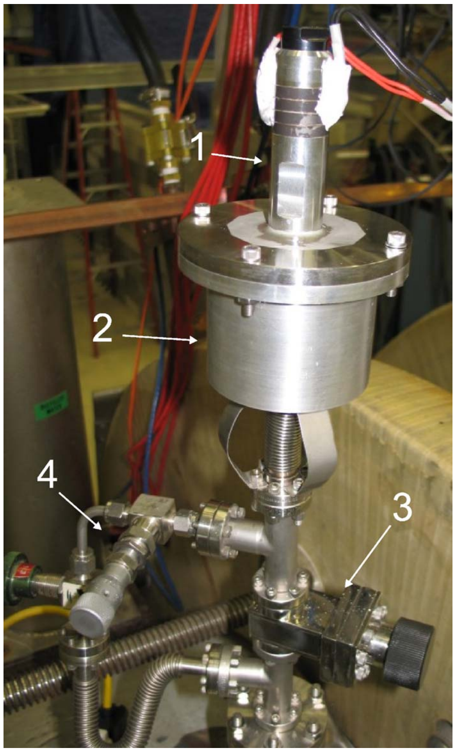

FIG. 3. (Color online) The dust dispenser is composed of the piezoelectric transducer (1), a cylindrical box (2), an isolating valve (3), and a needle valve (4).

D. Vacuum system and surge tank

For initial testing and performance evaluation the coaxial gun has been mounted on a large vacuum tank pumped down to 3×10^{-6} torr. However, when installed on NSTX, the plasmadynamic accelerator will be equipped with its own pumping system, which will include a roughing and a turbomolecular pump, with pumping rates of up to 100 L/s. A surge tank with a volume of about 1000 L and placed in between the NSTX vessel and the coaxial gun will restrict the flow of gas from the coaxial gun to the main plasma. While the hypervelocity dust grains will pass through the surge tank, most of the gas will be captured by the tank. Molecular flow calculations give a throughput of $\approx$3 mtorr L/s, considering that the initial volume of gas inside the coaxial gun will adiabatically expand in the surge tank. This value can be even further reduced by shutting down a fast valve after the dust grains have left the HDI.

III. DISCUSSION

A hypervelocity dust injector has been built to measure the topology of the internal magnetic field lines in plasmas produced in NSTX. Carbon micron-sized dust grains will be accelerated in a plasmadynamic coaxial gun at velocities of the order of several km/s and launched inside the hot plasma. The HDI's coaxial gun, power and control systems, and dust dispenser are presently undergoing testing at Los Alamos. The goal of HDI is to measure simultaneously the magnetic field lines' orientation inside the plasmas at multiple positions. The accuracy of the method will be compared to diagnostic techniques already implemented such as the motional stark effect-collisionally induced fluorescence (MSE-CIF).[2]

ACKNOWLEDGMENTS

The authors would like to thank Dr. T. Intrator, W. Waganaar, M. Kostora, P. Sanchez, and R. Renneke for useful suggestions concerning the design of the plasmadynamic accelerator and of the power and control systems, and D. Begay and R. Aragonez for building many of the HDI components. This work is supported by DOE Contract No. W-7405-ENG-36 through the Office of Science, Office of Fusion Energy Science.

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