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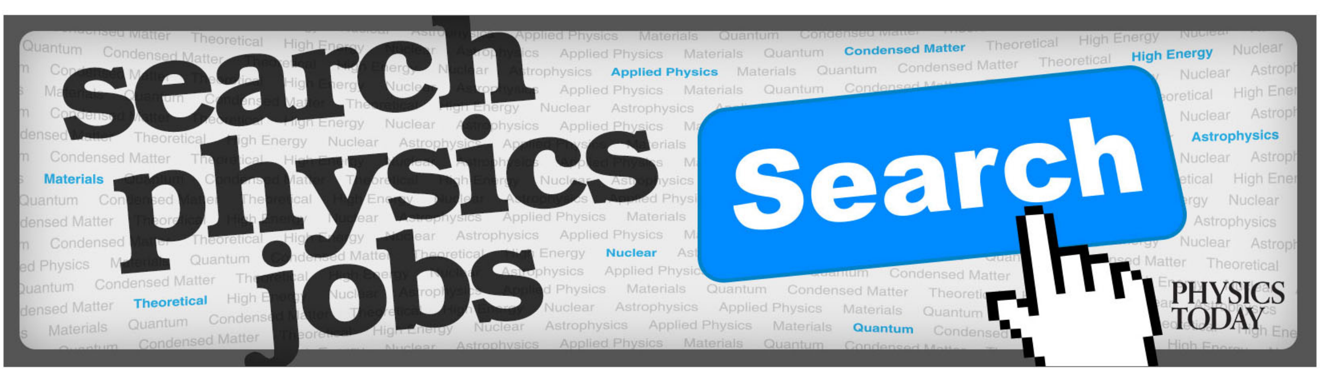

A compact and continuously driven supersonic plasma and neutral source[a)]

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A compact and repetitively driven plasma source has been developed by utilizing a magnetized coaxial plasma gun (MCPG) for diagnostics requiring deep penetration of a large amount of neutral flux. The system consists of a MCPG 95mm in length with a DN16 ConFlat connection port and an insulated gate bipolar transistor (IGBT) inverter power unit. The power supply consists of an array of eight IGBT units and is able to switch the discharge on and off at up to 10 kV and 600 A with a maximum repetitive frequency of 10 kHz. Multiple short duration discharge pulses maximize acceleration efficiency of the plasmoid. In the case of a 10 kHz operating frequency, helium-plasmoids in the velocity range of 20 km/s can be achieved. © *2010 American Institute of Physics.* [doi:10.1063/1.3483213]

I. INTRODUCTION

Particle injection techniques, e.g., gas-puff, neutral beam injection (NBI), and supersonic molecular beam injection,[1] have been applied to a variety of measurements combined with optical observation techniques, e.g., gas-puff imaging,[2] beam probing,[3] etc., for observation of high temperature magnetized plasma. However, the particles can only reach thermal diffusion velocity by the gas-puff technique and have difficulty penetrating into the core region of target plasma. NBI requires expensive facilities and the energy is usually higher than the keV range. Therefore, it is difficult to apply this technique to extremely high-beta (i.e., low confinement magnetic field) systems of field-reversed configurations because of shine-through loss.

Besides those common techniques, a new technique using a magnetized coaxial plasma gun (MCPG) has been proposed which can inject significant amounts of particles into hot magnetically confined fusion plasmas. The MCPG generates and accelerates a magnetized plasmoid, a so called spheromak or compact toroid (CT).[4] A plasmoid is accelerated by self-Lorenz force easily up to a hundred km/s and then is able to exclude and overcome the magnetic field of a tokamak. However, a significantly large plasmoid would perturb the confinement property of the target plasma. The MCPG with its long pulse discharge can generate magnetized plasma flow with large particle and helicity contents.[5] However, steadily injected magnetized plasma flow causes asymmetric opened magnetic configuration and negatively affects the plasma confinement property itself.

One of the ideal techniques of particle injection for the magnetically confined plasma is using repetitively injected plasmoids with sufficiently high repetitive frequency within the duration of discharge or target physical phenomena of plasma. Mostly as a fueling technique for tokamaks, repetitive operation of a MCPG has been tried at 0.2 Hz of frequency on the CT injection experiment at UC Davis[6] and 0.33 Hz at University of Saskatchewan.[7] Also repetitively generated plasmoids have been performed with a transformer coupled ringing discharge at Nihon University.[8] This paper presents an injector of even smaller physical dimensions but operation at much faster repetitive frequency of injection which has recently been developed at Nihon University.

The plasma gun is designed as small as what can be mounted on a standard DN16 ConFlat connection port. The discharge current is chopped by an insulated gate bipolar transistor (IGBT) inverter circuit at up to 10 kHz with changeable duty ratio. Generated small plasmoids are accelerated up to a few tens of km/s and then ejected from the MCPG, repetitively. Also, this technique can potentially be used as a supersonic gas injector through the charge exchange reaction in a drift tube.[9]

II. EXPERIMENTAL SETUP

A. Compact magnetized coaxial plasma gun

Figure 1 shows a diagram of a developed MCPG with a drift tube. The gun has compact geometry which can be mounted on a DN16 ConFlat flange of 34 mm in diameter. A set of inner (6 mm in OD) and outer (16 mm in ID) electrodes forms a single formation stage of the MCPG. The inner electrode made of stainless steel (SUS 316L) also works as a gas inlet tube into the discharge region.

A bias solenoid coil is wound directly on the outer electrode. The bias coil generates approximately 1.2 μWb of magnetic flux at 30 A of bias current. The operating gas is injected by a piezoelectric valve (Key High Vacuum Prod-

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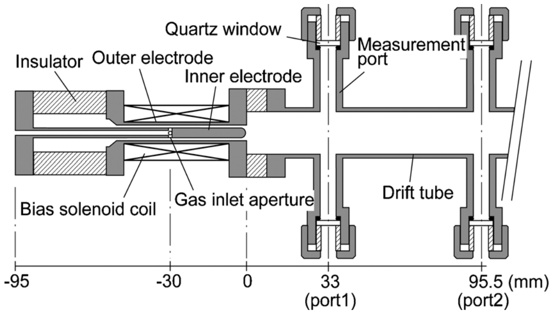

FIG. 1. Diagram of the magnetized coaxial plasma gun with a drift tube for time-of-flight measurement.

ucts, Inc., PEV-1) through the inner electrode and puffed into the gap between electrodes from the aperture on the inner electrode at $z=-30$ mm. The typical amount of injected gas is equivalent to 2.7 Pa of statically filled gas pressure.

The generated plasmoid is accelerated by self-Lorenz force and then toroidal current (poloidal field) is induced by the applied bias magnetic flux. In this series of experiments, helium-plasmoids have been generated because of their broad range of applications for measurements with the metastable states of helium.

B. Inverter discharge circuit

Discharge current is controlled by an IGBT inverter circuit. The circuit has been developed for general usage of inverter control of electrode discharges. Each IGBT stack has two series IGBTs (Nihon Inter Electronics Corp., PHMB600B12) and can be connected in series and parallel with other stacks for a variety of desired parameters. In this series of experiments, four series stacks (eight series IGBTs) have been employed. The inverter unit is specially designed for switching a large current discharge with a large turn-off surge between the coaxial electrodes of a MCPG. A specially optimized charging type snubber has been optimized for the wide frequency range of cutoff surges.

Figure 2 shows the diagram of the experimental setup with the equivalent discharge circuit. A capacitor bank of 48 μF is connected to the primary side of the circuit as a quasi-dc power source. Then, continuous dc input is chopped by an inverter circuit and supplied onto the plasma gun. Typical waveforms of discharge current and voltage for quasi-dc discharges and 10 kHz of repetitive operation with duty ratios $R_d=50\%$ (case 1) and $R_d=20\%$ (case 2) are shown in Fig. 3.

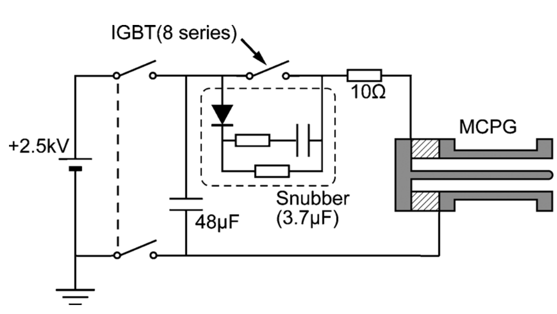

FIG. 2. Schematic of the experimental setup showing discharge circuit with the IGBT inverter switch.

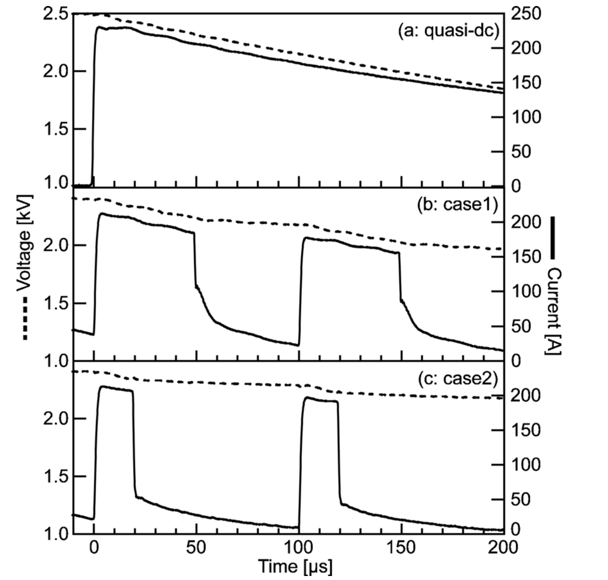

FIG. 3. Typical waveforms of discharge current and voltage on capacitor bank at (a) quasi-dc discharge, (b) case 1 (duty ratio $R_d=50\%$), and (c) case 2 ($R_d=20\%$) with 10 kHz of repetitive frequency.

Each current pulse has 2 μs of rising time and flattop with about 150 A (with slow decay limited by the capacitor bank). Repetitive frequency can be chosen up to 10 kHz and the smallest duty ratio is 20%, with 20 μs of pulse width (τ_p), at maximum frequency. The trailing edge has relatively long falling time of about 25 μs because of the time constant of the snubber circuit. However, a major part of the discharge current is cut off by the switching circuit. In this experimental condition, typical averaged input power on the plasma gun is approximately 380 kW (case 1) and 160 kW (case 2), respectively.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Initial experiments of highly repetitive MCPG operation have been performed on the experimental setup shown in Fig. 1. In this series of tests, dependency of translation speed on the pulse width has been estimated at the highest repetitive frequency of 10 kHz. Translation speed of plasmoids has been estimated by the time-of-flight (TOF) method along with the axially arranged optical measurement system.[10] The

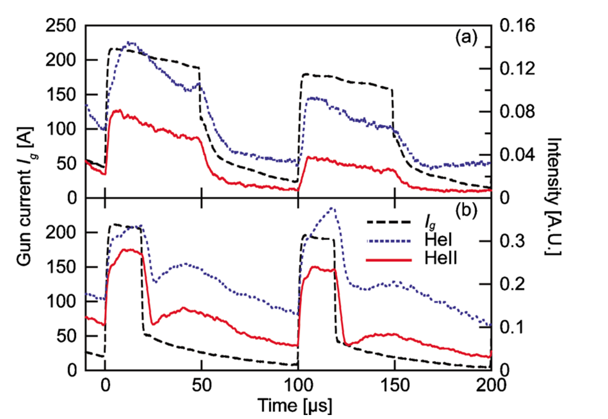

FIG. 4. (Color online) Typical waveforms of gun current, neutral (HeI), and ion (HeII) line spectra at $z=33$ mm at (a) $R_d=50\%$ and (b) 20%.

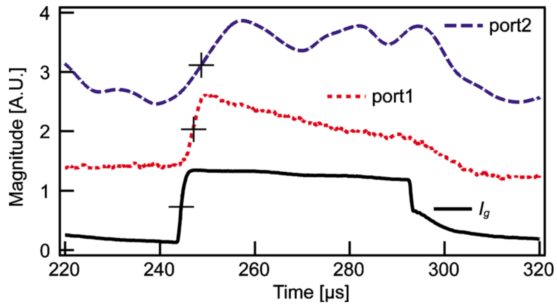

FIG. 5. (Color online) Enlarged typical waveforms of HeI emission and gun current for the TOF measurement.

optical filters have central wavelengths of 656 and 470 nm with bandwidth of 10 nm to measure line spectrum intensity of helium ions (HeII: 656 nm) and neutral particles (HeI: 470 nm), respectively. Typical waveforms of line emission intensity are shown in Fig. 4. These indicate successful formation and translation of plasmoids with the repetitive discharges. An enlarged waveform for a typical pulse in case 1 is shown in Fig. 5. The translation velocity between the MCPG and port 2 is approximately 22 ± 7.2 km/s for a 50 μs pulse. Here, the rising edge of the measured emission was taken at half-maximum as indicated by cross-shape marker in Fig. 5.

Typical electron temperature T_e and density n_e of generated plasmoids were estimated by the triple probe measurement at port 1 (Fig. 6). The electron temperature T_e stays at approximately 5 eV. Typical plasma density has a range of $0.8-1.6 \times 10^{20}$ m^{-3}. Therefore, the repetitive operation can provide approximately 2.3×10^{17} of particles per one millisecond in case 1. This amount of supplied particle is significantly enough for most of the magnetically confined plasmas for basic physics studies with microgram sizes of inventory and is also comparable to the compact low energy NBI system which has recently been developed.[11]

This MCPG system has been proposed as a supersonic neutral particle source through the charge exchange reaction process along the injection path. The travel distance which is necessary for the number of ions becoming 1/e due to the charge exchange reaction has been estimated for these helium and hydrogen plasmoid cases (Fig. 7). At a range of 20–30 km/s of translation velocity, 0.3 m of drift tube filled with 1.8×10^{18} m^{-3} of neutral particles can generate about 60% of neutral helium flow. This is a reasonably short length to be mounted between the target plasma and this injector system. This supersonic particle injector would be an alternative method for gas puffing.

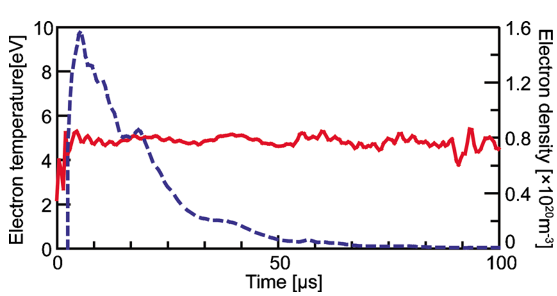

FIG. 6. (Color online) Time evolution of electron temperature (solid line) and density (dashed line) in the case of quasi-dc operation.

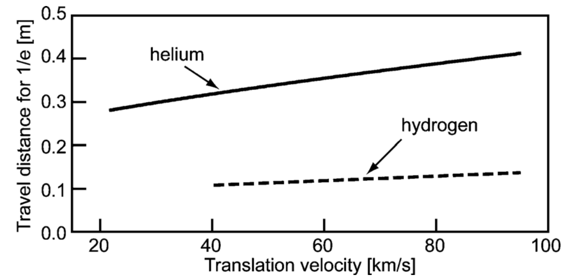

FIG. 7. The e-folding of number of ions on the travel distance to the translation velocity in a neutral gas atmosphere.

IV. SUMMARY AND NEXT STEP

A compact plasma and particle source with high repetitive operation frequency of 10 kHz has successfully been demonstrated. The developed system accelerated plasmoids up to the velocity range of 15–30 km/s. The achieved injection speed range is realized to generate neutral particle flow through the charge exchange reaction along a reasonably short length of drift tube. The presented system should be tested with hydrogen, deuterium, and argon gases for a wider range of applications, including fueling for various targeted magnetic confinement systems. The particle speed has to be double-checked by other measurements. Also the neutralization efficiency should be confirmed experimentally.

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