Laboratory demonstration of a bidirectional helicon plasma thruster for space debris removal

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Abstract: Space debris removal from Earth orbit by using a satellite is an emergent technological challenge for sustainable human activities in space. In order to de-orbit debris it is necessary to impart a force to decelerate it, resulting in its atmospheric re-entry. A satellite using an energetic plasma beam directed at the debris will need to eject plasma in the opposite direction in a controlled manner in order to maintain a constant distance between it and the debris during the deorbiting mission. By employing a magnetic nozzle plasma thruster having two open source exits, bi-directional plasma ejection can be achieved using a single electric propulsion device. Both the forces exerted on the thruster and the target plate simulating the debris are simultaneously measured in a laboratory space simulation chamber showing that a force decelerating the debris and a zero net force on the thruster can be successfully obtained. These two forces can be individually controlled by external electrical parameters, resulting in the ability to switch the acceleration and deceleration modes of the satellite and the debris removal mode using a single electric propulsion device.Nomenclature

I_{BL}	=	current supplied to the left solenoid
I_{BR}	=	current supplied to the right solenoid
C_{ArL}	=	gas flow rate from the left gas inlet
C_{ArR}	=	gas flow rate from the right gas inlet

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I. Introduction

SPACE debris orbiting around the Earth has become a serious problem over the past few decades; investigations into the mass distribution have shown a continuously increasing mass of debris [1]. To preserve a secure space environment and reduce the risk of collisions, the active removal, or de-orbiting of space debris is an emergent technological challenge. One of the important targets of the active removal is large space debris in the low Earth orbit (LEO), typically weighing about a ton and being a few meters in size [2].

If remedial action is not taken in the near future, it will be difficult to prevent the mass of debris increasing, and the production rate of new debris resulting from collisions will exceed the loss rate due to natural orbital decay [3]. Some concepts of space debris capture and removal have been proposed [4]; by using robotic arms and a tether net [5,6], a laser-ablation-induced material ejection from the debris [7], an orbit transfer using an electro-dynamic tether method [8], and an ion-beam shepherd (IBS) method [9] using two ion-beam sources.

Most of the contactless concepts (laser-ablation and IBS) have proposed imparting a force to the debris thereby decelerating them in a direction opposite to their velocity to transfer them to a lower altitude where they finally re-enter the Earth's atmosphere and naturally burn up. In the case of imparting a force to the debris by plasma ejection from a satellite using an electric propulsion device, such as the IBS method, the satellite is simultaneously propelled in the opposite direction, making it difficult to maintain the distance between the debris and the satellite. The IBS proposal would require two ion-gridded thrusters on the satellite, one of which imparts a force to the debris while the other balances the thrust by ejecting plasma in the direction opposite to the debris.

Another key technology for debris removal by electric propulsion is the control of the acceleration and deceleration of the satellite, which can be performed by adjusting the bi-directional plasma ejection. However, mounting two propulsion systems on the satellite will increase its development risk and make the satellite system integration more difficult due to weight and size considerations, which include the propulsion devices themselves, their power supplies and other necessary components (e.g., neutralizer, mass flow controller, etc).

For long-term operation of satellite for space debris removal, the lifetime of the propulsion device is one of the most important considerations. Operations of the ion gridded thrusters and the Hall thruster are known to be significantly affected by erosion of the electrodes and walls exposed to the plasma, especially for their high power operations. To overcome this problem, electrodeless plasma thrusters using magnetic nozzles (e.g., radiofrequency (rf) and helicon plasma thrusters [10-12] and a Variable Specific Impulse Magneto plasma Rocket [13]) have been investigated, where the high density plasma produced inside the source is transported to the source exit along magnetic field lines. Various types of plasma acceleration processes can occur, e.g., ion acceleration by a current-free double layer [14] and electromagnetic acceleration by an electron diamagnetic current [15]. Using a magnetic nozzle to increase thrust has recently been demonstrated by measurement of the force exerted on the magnetic field lines [16]. Experiments and simulations have shown that the thrust force is also affected by the neutral density profiles which affect the plasma density profile [17-19]. Measurement of ion energy distribution functions in a basic laboratory device has shown the spontaneous generation of supersonic ion beams on both the upstream and downstream sides of the plasma source [20].

In the present study a bi-directional plasma ejection from a magnetic nozzle rf plasma thruster having two open source exits is demonstrated in a laboratory experiment, where both the forces exerted on the thruster and a target plate simulating the debris are simultaneously measured. The measurement shows that by a judicious selection of experimental parameters, the force decelerating the debris can be imparted to the target while maintaining a zero net force on the thruster. This is accomplished by varying either the magnetic field configuration or propellant gas flow rates using two gas inlets located left and right of the source center. Consequently, the present rf plasma thruster can produce all three required operational modes in ONE electric propulsion device; the debris removal mode, the acceleration mode and the deceleration mode of the satellite, the latter two being useful for adjusting the satellite velocity relative to the debris.

II. Experimental setup

The experiment is carried out with the magnetic nozzle rf plasma thruster having two open source exits on the left- and right-hand sides. The thruster consists of a 6.5-cm-inner-diameter 20-cm-long glass tube, two solenoids, and a rf antenna; the whole structure is attached to a pendulum thrust balance immersed in a 1 m diameter and 2 m long vacuum chamber. A schematic of the setup is shown in Fig.1a. Argon gas is introduced from two gas inlets on the side wall of the source tube at z = ±5 cm with a total mass flow rate of 100 sccm, where the mass flow rates from the left and right inlets (C_{ArL} and C_{ArR}) are individually controlled by two mass flow controllers. Two solenoids located

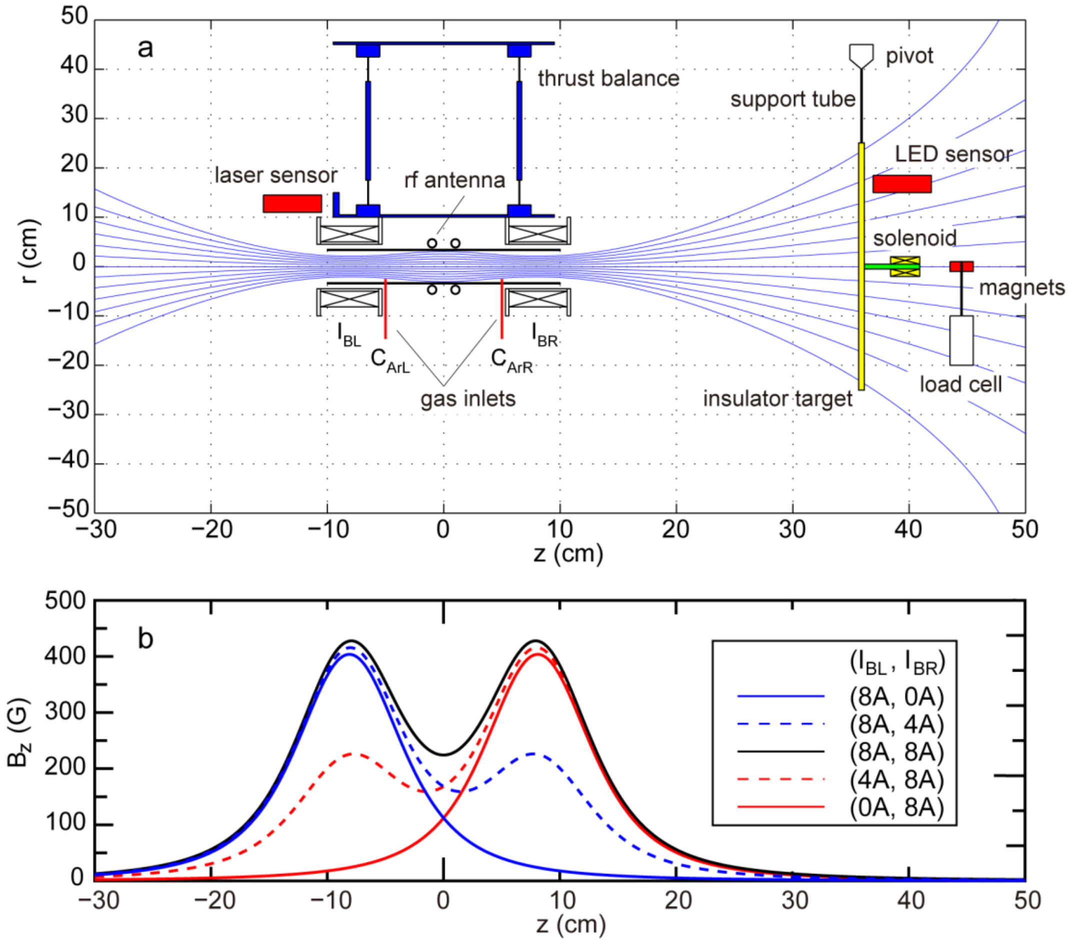

Fig.1: (a) Schematic diagram of the experimental setup, together with the calculated magnetic field lines for the (I_{BL}, I_{BR}) = (8 A, 8 A) Left/Right solenoidal current case. (b) Calculated magnetic field profiles on axis for various combinations of *(I_{BL}, I_{BR})*. The figure is taken from Ref. [24].

near the two open source exits provide a magnetic field and the field configuration can be changed via the dc solenoid currents (I_{BL}, I_{BR}) as shown by the calculated magnetic field in Fig.1b. A shielded double-turn rf loop antenna [21] is situated at the axial center of the source tube (defined as z = 0) and powered from a 13.56 MHz, 1 kW rf generator, producing a high density plasma. Axial forces are imparted to the mechanical and magnetic structures of the thruster via momentum transfer by the ions interacting with the radial wall [17] and by the Lorentz force on the magnetic field due to the plasma-induced electric current [15,16]. The thrust force exerted on the thruster by the plasma is obtained by measuring the displacement induced by the plasma ejection [22]. A 45-cm-diameter pendulum target plate simulating the debris is suspended from a pivot located at z = 35.9 cm downstream from and to the right of the thruster, and the force exerted on the target plate is obtained from its measured displacement combined with a calibration coefficient relating the displacement to the force [23]. The direction of both the forces and the displacements is defined as positive for the rightward direction. The absolute values of the forces can be obtained by multiplying the calibration coefficient to the measured displacements.

III. Experimental results

Figure 2a shows photographs taken via a vacuum view port on the chamber side wall for solenoid currents of (I_{BL}, I_{BR}) = (8A, 0A), (0A, 8A), and (8A, 8A), with the gas flow rates from the two gas inlets respectively set at 50 sccm yielding a total flow rate of 100 sccm. A brighter plasma plume is seen on the left and right sides for the (I_{BL}, I_{BR}) =

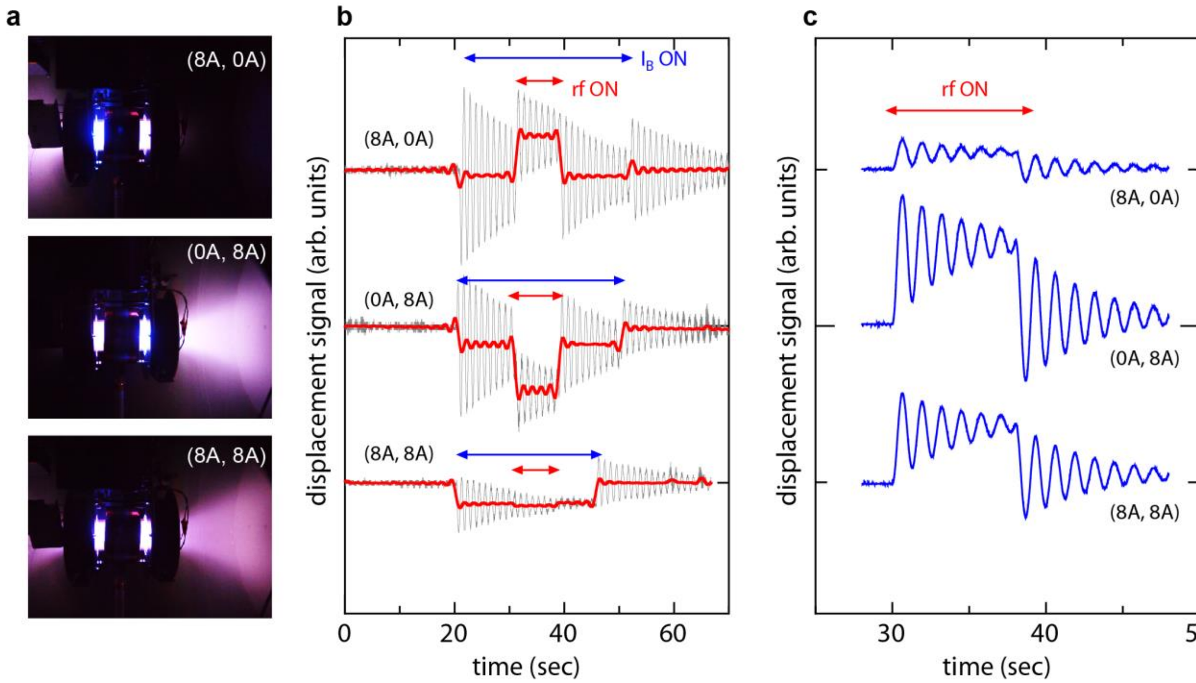

Fig.2: (a) Photographs taken by a digital camera via a vacuum viewport on the chamber side wall for the solenoid currents of (I_{BL}, I_{BR}) = (8 A, 0 A), (0 A, 8 A), and (8 A, 8A). (b) The raw (gray thin lines) and filtered (red bold lines) displacement signals of the thruster attached to the thrust balance. (c) The displacement signals of the target plate. The positive and negative displacement in Figs. 2b and 2c corresponds to the rightward and leftward directions, respectively. The figure is taken from Ref. [24].

(8A, 0A) and (0A, 8A) cases, respectively, while bi-directional plasma plumes are observed for the symmetric magnetic field configuration of the (I_{BL}, I_{BR}) = (8A, 8A) case. The displacement signals of the thrust balance and the target plate for these conditions are shown in Figs. 2b and 2c, respectively. For the (I_{BL}, I_{BR}) = (8A, 0A) and (0A, 8A) cases shown at the top and middle of Figs. 2b and 2c, the thruster moves toward the right and the left respectively, demonstrating that changing the magnetic field configuration engenders the deceleration and acceleration modes respectively, while the target is always pushed towards the right. For equal solenoid currents, (I_{BL}, I_{BR}) = (8A, 8A), a symmetric magnetic field configuration is produced; the target plate moves to the right while a zero displacement of the thruster is maintained (bottom panels of Figs. 2b and 2c). These results show that this bi-directional rf plasma thruster can provide the three operation modes necessary for space debris removal.

In order to perform space debris removal in the space environment surrounding the Earth, the acceleration and deceleration of the thruster, the relative velocity with respect to the debris, and the force on the debris have to be precisely controlled by some external parameters. Figure 3 shows the measured forces on the target (Figs. 3a and 3b) and on the thruster (Figs. 3c and 3d) as a function of the currents supplied to the right and left solenoids (I_{BR} and I_{BL}); when the current through one solenoid is changed and the current in the other solenoid is maintained at 8 A. It can be seen that for equal solenoid currents of 8 A, (the symmetric magnetic field configuration) the thruster experiences a zero net force while a force of ~8mN is brought to bear on the target.

Interestingly, the force on the thruster can be changed, as seen in Figs.3c and 3d, demonstrating that the bi-directional thruster is operational for both the modes of thruster acceleration (negative left directed force) and deceleration (positive right directed force). Between these three conditions, both the forces on the target and thruster continuously change when the solenoid currents are adjusted, resulting in a considerable degree of control of both forces. Additionally, the force to the target for (I_{BL}, I_{BR}) = (8A, 8A) case and the thrusts for (I_{BL}, I_{BR}) = (8A, 0A) and (0A, 8A) cases are very similar in the range of 8-10 mN; implying that the operation modes can be switched while

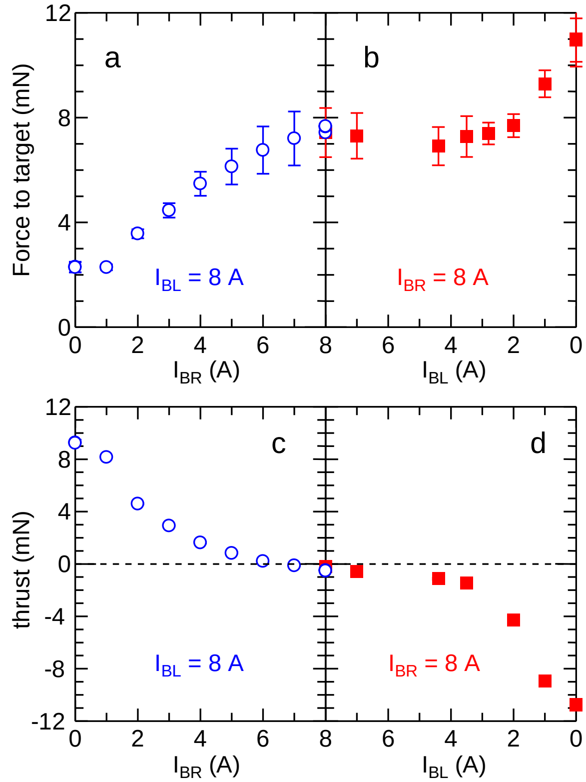

Fig.3: Simultaneously measured force to (a,b) the target and (c,d) the thruster as functions of the right- and left-hand solenoid currents (I_{BR} and I_{BL}). Either of these two solenoid currents is maintained at 8 A when surveying the other one. The figure is taken from Ref. [24].

maintaining both the effective utilization of the gas propellant and the rf power. This has been previously published in Ref.[24] and the details will be presented.

Conclusion

Laboratory experiments have shown that bi-directional plasma ejection from an open exits magnetic nozzle rf plasma thruster can impart a force to space debris whilst maintaining a zero net thrust force to the thruster (and satellite). The simultaneous measurements of the forces to the thruster and the target plate show that the two forces can be controlled by the magnetic field configuration and/or the gas flow rates from the left and right gas inlets respectively. Therefore, the system can be operational in three modes; the acceleration mode of the satellite, the deceleration mode of the satellite, and the space debris removal mode.

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