Visualization and simulation of ion thrusters possibly usable by small satellites

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***Abstract*—After launching a small satellite and placing it into its final orbit, it can have unwanted and uncontrolled rotation. Therefore a small satellite needs to perform some maneuvers to stabilize or slightly change its position on its orbit. Due to its small size it needs only a small drive system and torque to stabilize. Furthermore, the available energy for attitude control is also limited. Ion thrusters use ionized neutral gases accelerated by electric field to drive the spacecraft or change its attitude. As ionized gas flies out of the thruster it makes an opposite directed force. If we use different outlets for ions to fly out from thruster it can act like a three dimensional steering system.**

A process of finite element based solution is used to calculate quasi-electrostatic field of the internal the thruster. It is also used to perform simulations on the outlets. Using the field calculated we can show possible allowed and forbidden paths of ions spreading inside and outside of the outlets.

We present a visualization technique to show the internal world of a possible three directional steering system. Visualization of our results is import to understand operation of device and find possible improvements. Also it can be used to illustrate internal operations of the thruster for educational purposes.

***Index Terms*—simulation, visualization, ion thruster, small satellite, steering**

I. INTRODUCTION

The launch system of a spacecraft is a complex structure and it consists of typically several rocket stages that often use different propulsion systems. A typical and commonly applied structure can be observed in the Ariane rocket family [1].

Usually high-power booster(s) with solid propellant can be found in the first stage, extended with a cryogenic core stage with liquid propellant. The boosters are operating in the first launch phase for a couple of minutes and after the separation are returning to the ground for later reuse. The main stage operates up to its separation when the spacecraft's performance value an appropriate height and speed reached. At this point the upper stage is ignited to place the payload(s), e.g. satellite(s) to their final orbit. Ariane 5 is designed to carry satellites to Geostationary Transfer Orbit (GTO), sun synchronous and polar circular orbits, elliptical or International Space Station (ISS) orbit, but there is a version for Earth escape missions as well. The above-mentioned rocket engines are providing very high thrust in the MN-kN range: the boosters 7000kN, the core stage more than 100kN and the upper stage 67kN. A typical GTO mission has approximately 30min duration.

When we talk about an individual satellite that already reached its planned height and speed by the launch system, a subsystem of the satellite, the propulsion system is supporting the spacecraft's further orbital maneuvers and changes its position by firing thrusters. Depending on the mission's type, the task of the propulsion subsystem may perform apogee injection e.g. to reach a final geostationary orbit. For that one a few hundred of N thrust level is required. In order to perform minor orbit control, like modifying the inclination, maintenance of the orbit low power thrusters with few times 10N is required.

The orientation of a satellite should be also controlled in order to maintenance of the spin rate, perform axes stabilization or rotate the satellite to a specific direction. This kind of maneuvers requires a few N of thrust.

The propulsion subsystem of satellites have many different operating principles. Chemical propulsion systems with monopropellants or bipropellants may provide higher thrusts. However, the resulted chemical products may influence the external environment of the spacecraft and it could be intolerable by the mission's goal, especially when there are sensitive measurement devices among the payloads.

Cold gas systems with neutral gases are operating in the lower power ranges. The primary choice is nitrogen as its relatively high molecular size prevents the fuel leakage. An alternative propellant is argon, when nitrogen cannot be applied for specific reasons.

The electric propulsion systems are using ionizable gases as the propellant. Electrical power supplied by an external energy source is used to accelerate the propellant to extreme velocities and thereby achieve very high specific impulses. However, the power as well as the thrust is limited by the available electrical energy delivered by batteries, solar generators or radioisotope thermoelectric generators (RTGs). The electric propulsion systems have very low thrust, comparing to the previous methods. Thrusters for electric propulsion require propellants which can be easily evaporated and ionized and which have a high molecular weight. Therefore the development of thrusters for electric propulsion concentrated on the use of inert gas xenon, which can be stored in high-pressure gas tanks. Xenon has a high molecular weight and can be

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quite easily ionized. The idea of electric propulsion is not new - NASA Glenn Research Center has been a leader in ion propulsion technology development since the late 1950s, with its first test in space - the Space Electric Rocket Test 1 – flying on July 20, 1964 [3]. In [4] and [5] the principles of operation and the several types of thrusters that are either operational or in advanced development are discussed. Ion thrusters (based on a NASA design) are now being used to keep over 100 geosynchronous Earth orbit communication satellites in their desired locations and there are other missions with electric propulsion system as well.

In this paper we provide a finite element based solution to calculate quasi-electrostatic field of the internal the thruster and we perform simulations on the outlets. The applicability of this thruster method for small satellites is also investigated.

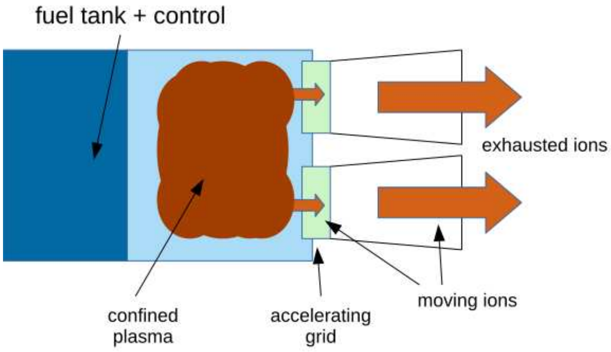

Fig. 1. Schematic of an ion thruster engine

The organization of this paper is as follows. Section II, gives a general overview of principle of operation of ion engine we simulate later. We give a short introduction to interior of an ion engine. Section III describes simulation steps and assumptions. Section IV shows results on the jet formation effect of engine nozzle simulations. Finally, section V concludes the paper.

II. PRINCIPLE OF OPERATION OF SIMULATED ION ENGINE

A. *Types of electric propulsion engines*

Electric propulsion (EP) can be categorized by many ways. First types is the ion thrusters when only electric field to accelerate ions (see Figure 1). The other type is that use magnetic field and electric field to accelerate and control ion or plasma jets [5]. This type is more sophisticated and due to its size it is not possible to implement in a Cubesat environment.

Both types use electric field acceleration grid (AG). It is formed as two grids separated from each at a few centimeters and potential difference made between. On one grid ions comes in and on the other grid leaves it with a higher speed.

B. *Electric propulsion system proposed*

We are propose a simple electric propulsion system for small satellites. These EP system is based on the basic principle that we accelerate the gas (ions) that moves outward of the spacecraft will thrust the spacecraft to the opposite direction. The gas must have charges (ionized) to be accelerated by electric field.

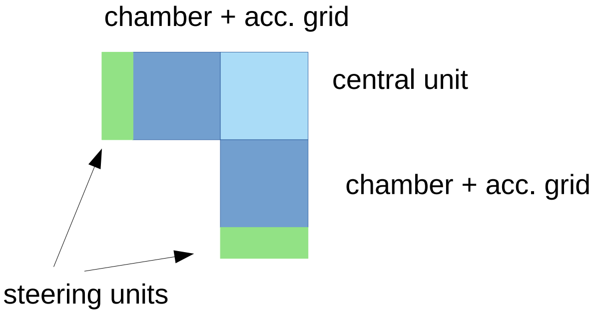

Fig. 2. A possible system usable on small satellites for steering using only fuel tank and control unit (light blue box), two chambers and acceleration grids (blue boxes) and two steering units (green boxes). Great boxes are 1U sized, green boxes are 0.5U sized.

Our model is based on a simple discharge chamber where gas is ionized and an acceleration grid that moves ions outward. Control of ion jets are performed using electrodes attached to nozzle inner surface and driven by potential.

In this paper we analyze control of movement of ion jets inside the nozzle through only electric field.

C. *Possible system for Cubesat steering*

Cubesats have a limited space and mass. Currently there are spinoffs that offers a plan for 2 unit large propolsion systems based on Xenon or Iodine [8].

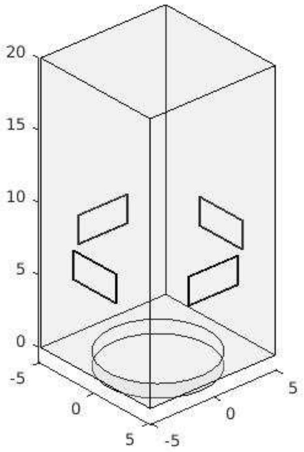

Fig. 3. Outline of the nozzle. Small rectangles on the sides are control electrodes. The tube on the bottom is the upper side (top side) of the acceleration grid. The top of the grid is connected to zero voltage. The potential of the electrodes is used to control ions movements.

If we assume that this system works, an additional steering mechanism can be used for steering. It is based on deflecting ions that fly out from thrusting. The deflector system can bend the beams, and thereby it can help to maneuver the satellite. The system is shown on Figure 3. The rectangular formations are electrodes of the deflector system. It can turn the ion beam and thereby it can turn the satellite too.

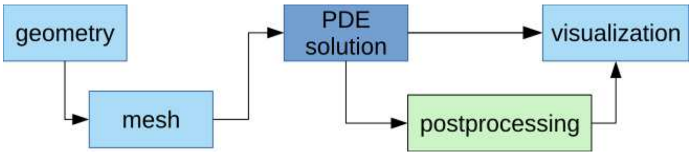

Fig. 4. Chain of simulation

III. Simulation background and Layout

A. Background of simulation

We start our model when ionized plasma paces the accelerating grid and enters nozzle region. Principle of ions motion is determined by Newton's law. Force of action is specified by electric field caused by electrodes (control electrodes) placed on the hull of nozzles. We use the outer grid (negative grid) as a nearly zero potential electrode. The nozzle hull's electrode has a higher potential (about the same magnitude as the inner grid which is on the inner side of the accelerator). The hull's region and the control electrodes are shown on Figure 3.

In the model the accelerator grid is not included. We take its effect into account through the speed of ions that enters the nozzle region. Top of accelerator grid is connected to zero potential while the control electrodes has a higher potential (in the few kV range). Interaction between the ions are not taken into account. Effect of outer magnetic was also not investigated.

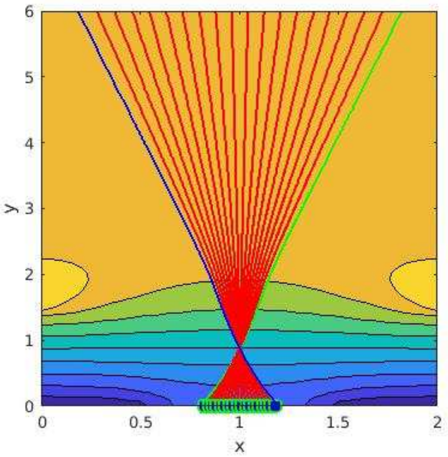

Fig. 5. Path of ions in case of symmetrical driving

B. Steps of simulation process

Steps of simulation process is shown on Figure 4. Our goal was to use as much free software as possible. Therefore only for solution of the finite element model was used commercial software. Geometry and mesh generation was made using gmsh [9], visualization was performed using Paraview [10]. While gmsh and Paraview are free software they have a lot features usable for 3D simulation.

Solution of the partial differential system (PDE) is the main part of simulation chain. It solves Laplace-equation of electrostatic potential caused by electrodes which are used as boundary conditions using finite-element method (FEM). A FEM solver needs a good mesh for solution. Using result of FEM solver we calculate possible ion paths starting on top of grid with a given velocity. As part of the project we implemented an import function for Paraview that enables us to export solutions of FEM (solved using Matlab). Since solution of FEM model is the electrostatic potential we calculated path of moving particles starting at the top of acceleration grid.

IV. Results of simulations

Our simulations were performed on 2-dimensional structures. Because the structures have symmetries it was a good idea to use them. As our expectations are fulfilled by 2D results, it can be extended to 3-dimensional cases.

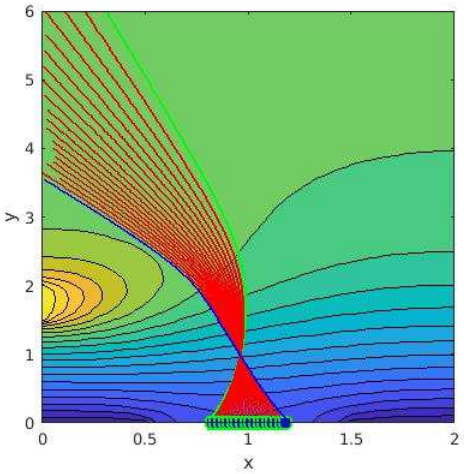

Fig. 6. Path of ions in case of using guided electrodes. Path of ions (red) and equipotential lines of electric field are shown.

Analyzing the possible structures we found that only small region in the middle can be used to start ion beams. We examined the motion of different ions, Xenon and Iodine ions were used. It is found that it has no essential difference between the two possible fuels.

A. Effect of electrodes with free unguided electrodes

First we use a simple non-guided case as reference. Non-guided or symmetrically guided means that the control electrodes have the same potential. The results are shown on Figure 5. Equipotential surface (lines) are shown (smaller potential means more blue). The path lines of ions started from the green region on the bottom. There is an extra acceleration introduced through the control electrodes while the ion jet gets a splayed cone shape as shown on Figure 5.

With no guidance, we have an ion beam directed outward. As we use different potentials on the control electrodes, we can inflect the beam toward the electrode with the higher potential, as shown in Figure 6.

The spread of ion jet is smaller in this case (we used the same starting points of ions as before). The main direction of the beam is bent about 20o compared to the unguided case. Surprisingly the bending has a maximum at the shown angle.

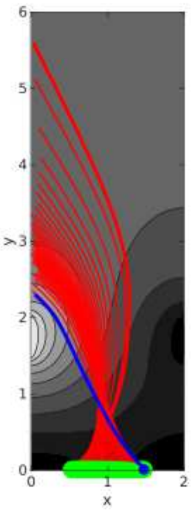

Fig. 7. Effect of connecting unguided electrode to the same potential as top of acceleration grid

And this limit is reached at a relatively low electrode potential of a few hundred Volts in case of average acceleration.

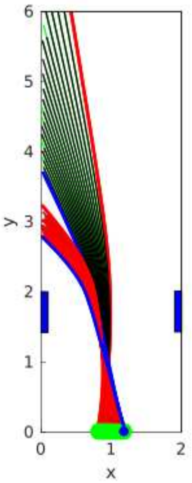

Fig. 8. Trace of ions (red – when other electrodes are connected; black – when not-connected) and equipotential lines of the electric field

B. *Effect of connecting unguided electrodes*

It is possible to connect unguided electrodes to the same potential of the top of accelerating grid. In this case we get into a different situation. As shown in Figure 7 connection produces a higher gradient in potential as in earlier case. As a consequence a higher electric field is produced that affects ions. The stronger field produces a higher rotation on the beam.

Rotation of ion beams are shown on Figure 8. Ions are started at the green region with an average speed of 10000 m/s. As they fly to the nozzle region the direction of electric field changes drastically and directs them in the direction of driving electrode. Because the ions have a large speed thus they fly over the electrode and pop out from nozzle. The thrusting force of this acceleration grid can make about 5-20 mN force depending on the expended amount of fuel.

If we connect the unguided electrodes to the same potential like that the top of AG, the ions are deflected more than in case when unguided electrodes are not connected to anywhere.

V. CONCLUSION

We presented first results of a control system that can control ion thruster's ion beam using only electric field. The effect of guiding electrodes can be controlled by the magnitude of electrode potential and connection status of the the other electrodes. It is found that thrusting material doesn't affect the ability of control.

It was presented that the ion beams can be controlled only by the electric field. Out future work is to show that this control mechanism can be used to guide the beam to any direction in a conical shape.

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