Innovation in the development of plasma propulsion devices in Israel

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Abstract. In this paper we review plasma propulsion development approach which focuses on innovation. We then bring the example of the state of Israel in general, and Rafael in particular, and show how it has adopted an innovative approach to develop a low power Hall thruster and a low current cathode. To present one special test-case of innovation we elaborate upon the development process of a heaterless hollow cathode that was developed at Rafael. In particular, by presenting the cathode characterization and wear test results we demonstrate that the heaterless cathode developed has a sufficiently wide operational range and may operate continuously for 1,500 hours without any measurable degradation in performance.

1. Introduction
Plasma propulsion is a particular plasma application in which gas is ionized and accelerated through applied electric and magnetic fields with the ultimate purpose of generating momentum for spacecraft maneuverability [1]. Using plasma propulsion over a hundred different spacecraft, mainly communication satellites, maintain their trajectories in space [2] and many more are expected to be launched in the upcoming decade [3]. Unlike chemical propulsion, that harnesses its energy from the chemical bonds within the propellant; and therefore is energy limited, plasma propulsion is limited only by the electrical energy supply on-board the spacecraft. As such plasma propulsion can be used to accelerate propellants to velocities much higher than with chemical propulsion. Consequently, plasma propulsion is more propellant-efficient than chemical propulsion and sees an increasing use over the past few decades [4]. In particular, the use of plasma propulsion for communication satellites has increased by approximately 800% between 1995 and 2011 (Figure 1) due to the significant propellant mass savings compared with conventional chemical propulsion [4].
This ever-growing popularity of plasma propulsion drives many commercial entities to develop, manufacture and eventually offer plasma propulsion based systems for satellite platforms. However, due to the high capital and professional training requirements associated with the development of such systems these commercial entities have traditionally been subsidized by large financially-capable countries. As a consequence, only large geo-political entities, such as the US, EU, Russia, Japan and China, have produced full scale plasma propulsion capabilities which are being leveraged on to dominate the commercial plasma propulsion market. Nevertheless, one possible key approach taken by technologically oriented yet “ill-funded” entities to enter the plasma propulsion market is by offering innovative solutions for existing needs. Through innovation technological, thus commercial, advantage may be gained; therefore allowing new players to enter an existing plasma propulsion market.

In this paper we briefly discuss the innovation approach. We then bring two examples of innovative plasma propulsion devices developed at Rafael, Israel. Lastly, we focus and elaborate on one specific device by presenting a test-case of an innovative technical approach – the development of a heaterless hollow cathode that is conducted at Rafael.

2. Innovation approach
To succeed in penetrating an existing space market, which is largely dominated by large technologically-capable geo-political entities, small countries may seek to find innovative and alternative solutions to existing ones. In this approach the developer eliminates the notion of seeking conventional or traditional technical solutions, under the assumption that developing similar devices as already exist in the market will hinder future marketing efforts. Instead, the developer looks for new variations of traditional technological solutions, in combination with new technologies, which may out-perform existing solutions. Improvement on traditional technological configurations requires different thinking and innovation; whether from physics or engineering points of view. In this way small companies may gain technological advantages that outweigh the advantages of space-proven technologies.

The state of Israel, being a technologically-oriented yet a relatively ill funded geo-political entity, serves as a good example of a country practicing the innovative approach. We hereby present two particular examples of innovative plasma propulsion devices developed at Rafael, Israel. These are (1) CAM200 low power Hall thruster and (2) Rafael’s heaterless hollow cathode neutralizer.

The developments of the two main components of Hall thruster based propulsion systems, namely the Hall thruster and the cathode neutralizer, include unconventional design that pose a physical advantage over the conventional configurations (Figure 2).
Israel’s activities in the field of plasma propulsion began in the late 90’s at Soreq where basic low power Hall thruster research was carried out at an academic level [5]. During the first decade of this century all activities migrated to Rafael and the Technion [6] while building on the work and achievements gained a decade earlier. Since low power Hall thrusters already existed in the world at that time [7] a different thruster configuration was conceived, and later patented [8] to give the thruster better attributes compared with his low power Hall thruster cousins. The CAM200 Hall thruster, developed by Rafael, consists of co-axial anodes [9] (Figure 3). The special anode configuration enables more efficient thruster operation than conventional Hall thrusters – making the thruster more attractive to potential customers.

Using theoretical, numerical and experimental investigations it was shown that the co-axial anode configuration modifies the electric field pattern within the thruster channel, acting to repel the ions from the thruster walls. This effect leads to ion beam focusing which gives a strong axial momentum component to the ejected ions. Ultimately, the well-directed ion beam carries a higher fraction of the input power to the thruster relative with other low power Hall thrusters; leading to higher efficiency. In addition, it was recently shown that CAM200 performance envelope is similar to high power Hall thrusters – the most efficient “members” of the Hall thruster device family [10].

CAM200 thruster development continues to date within the frame of the Micro-satellite Electric Propulsion System (MEPS) project. The aim of the project is the development and qualification of a low power plasma propulsion system. The project is a joint development activity between Israel and Europe [11]. In particular developers from Israel, Italy and Greece are in charge of the design, manufacturing and testing of the developed system. Within the frame of the MEPS project component responsibilities are distributed between the different parties, as well as financial responsibilities.
Future development phase shall include environmental tests, thruster lifetime experiment and plasma propulsion system integration tests.

The cathode neutralizer consists of a heaterless configuration that enables fast ignition along with higher reliability. In the next section we elaborate on the cathode development process.

3. Test-case for innovation – the heaterless hollow cathode
To further illustrate the 'innovation' approach mentioned above we present a test-case – the development of the heaterless hollow cathode that is conducted at Rafael. We first explain the different technological mechanisms of heaterless hollow cathodes compared with conventional cathodes. We then overview the development cycle of the heaterless hollow cathode and conclude by outlining the characterization and lifetime qualification tests of the cathode.

3.1. The role of the cathode neutralizer for plasma propulsion
The cathode neutralizer (Figure 4) is an electron-emitting device that serves three main functions: (1) supplying sufficient stream of electrons for the neutralization of the ion beam coming out of the thruster, (2) serving as the negative terminal of the electric propulsion circuit and (3) igniting the thruster-cathode module [12].

![Figure 4. Basic configuration of a hollow cathode neutralizer for plasma propulsion applications.](image)

The most important component within the cathode is the electron emitter, sometimes referred to as *insert* in literature. The emitter is made of a low work function material that emits electron flux in the order of ~1 A/cm² at relatively moderate temperatures of over 1,000°C [13]. Since for the thruster to operate the emitter has to be at this temperature both pre-heating of the emitter and proper cathode thermal design are required. The traditional emitter-heating method is by a dedicated heater element wrapped around the emitter tube. Prior to cathode ignition the heater is turned on and the emitter brought to its operational temperature and cathode ready to be turned on with the thruster. In many cathodes the thermal design is such that after thruster ignition sufficient heat flux from the cathode discharge maintains emitter temperature and the heater is no longer required.

In general, cathodes neutralizers should emit the amount of electron current required by the plasma thruster. As such cathodes tend to scale up or down with the thruster – low power Hall thrusters require low current cathodes.

3.2. Basic principles and advantages of heaterless hollow cathodes
Heaterless Hollow Cathodes (HHCs) are a subclass of hollow cathodes that do not require external heating to heat up the electron emitter to its operation temperature. Instead of using external heating HHCs use a unique ignition technique. Firstly, high voltage pulse is applied between the emitter and keeper (Figure 4) so to electrically breakdown the injected gas. Immediately after initial discharge creation a separate power supply controls the emitter-keeper current, a process during which the emitter is heated. The heating process lasts until the emitter reaches its operation temperature. Lastly,
after steady discharge has been initiated the electric thruster is turned on by applying the required emitter-anode current. The entire thruster ignition duration is usually less than 100 seconds.

Since HHCs do not use external heating for ignition they possess advantages over their heater-utilizing cousins. First, in comparison to heater-utilizing cathodes that have typical readiness time in the order of minutes, due to the required heating duration, HHCs reach steady-state operation within tens of seconds. Secondly, since no external heating is required the Power Processing Unit (PPU) does not contain the corresponding heater module, therefore lowering its mass. Lastly, since cathode heaters usually contain refractory metals and experience extreme thermal cycling they are susceptible to thermal failure. HHC combat this problem by completely removing the ignition dependence on heaters.

HHCs have been explored for over four decades [13] in various locations around the globe. Most work was academic in nature and performed by either universities or research entities. Some work was presented by space industries or government agencies, yet little follow up literature exists from these attempts that most likely had no continuation. Nevertheless, in recent years there is a regrowing interest in HHC technology, an interest that might lead to maturation of the technology ending in space proven hardware.

### 3.3. The development cycle of the HHC at Rafael

Due to the technological advantages mentioned Rafael began its cathode development process by designing and investigating various ignition and operation techniques of HHCs. The ultimate purpose was to design a cathode able to supply discharge current of 0.5-1.1 A so to neutralize the ion beam ejected out from a low power Hall thruster. The development cycle (Figure 5) included the following phases:

1. **Design** – in which the mechanical structure of the cathode was modelled with CAD methods.
2. **Simulations** – in which the plasma discharge within the cathode was modelled and cathode’s thermal and structural behaviours simulated.
3. **Manufacture** – in which the cathode parts and components were manufactured and jointing processes developed.
4. **Experiments** – in which the cathode hardware was experimented on in laboratory environment.
5. **Analysis** – in which the experimental results and cathode post-operation structure were adequately analyzed and conclusions drawn.

![Figure 5. The development cycle of the heaterless hollow cathode as carried out at Rafael.](image)

After the analysis phase conclusions drawn and lessons learned fed into the design phase and the cycle continued until desired cathode operation was achieved.
3.4. Cathode characterization and qualification

The development cycle converged into the most recent heaterless hollow cathode design (Figure 2). After verifying adequate and satisfactory cathode operation, two advanced operation verification phases were carried out – cathode function characterization and cathode 1,500 hr wear test [15].

During the characterization phase cathode operation was monitored for different operational parameter values; namely mass flow rate and discharge current. In particular, floating keeper-emitter voltage was monitored to assess cathode sheath variations with the operational parameters [16]. The measured results are presented in Figure 6. The floating keeper-emitter voltage gives indication for the cathode "health level"; high voltage indicates an insufficient ion flux into the emitter surface and implies on possible cathode operation limitations. Additionally, large voltage fluctuations indicate on possible ion acoustic turbulence which consumes power from normal cathode operation in favour of an external ion energy increase [17].

The characterization process assures adequate cathode operation within the pre-defined limits and depicts cathode behaviour limits.

After the completion of the characterization process it was necessary to prove the ability to operate the cathode continuously throughout the projected lifetime of approximately 1,500 hours. For this reason a 1,500 hour cathode wear test was executed. During the wear test the cathode was operated continuously in a 24/7-manner while several electrical and thermal characteristics were tracked and recorded. In particular two cathode operation properties were monitored – (1) floating keeper-emitter voltage and (2) cathode keeper external temperature. The former gives indication on the electron emitter vitality and whether it reached its end-of-life. In case of emitter depletion its work function is expected to rise [18] leading to rise of cathode voltage, hence rise of floating keeper-emitter voltage [19]. The latter also indicates on the electron emitter vitality as any increase in emitter work function leads to an increase in steady-state emitter temperature which will increase the temperatures throughout the cathode body.

Floating keeper-emitter voltage and cathode keeper temperature plotted against elapsed time over the course of 1,500 hours are presented in Figure 7. It can be observed from the figure that throughout the entire cathode wear test its operation is stable and does not deteriorate. We therefore conclude that the cathode has expected lifetime of over 1,500 hours.
The successful completion of both the characterization and wear test phases gives the confidence that the developed product meets any expected requirements of such device. Using the development methodology described above the risk of innovation was mitigated and a new space commercial device was born.

4. Conclusions
In this paper we discussed the innovation approach for plasma propulsion device development used to produce cutting-edge solutions that outweigh the existing ones. We brought the example of two device developments carried out in Israel and showed the innovative technological features of each one. To present one special test-case of innovation we elaborated upon the development process of a heaterless hollow cathode that was developed at Rafael. In particular we showed the characterization and wear test phase experimental results. The data proves that the heaterless cathode developed has a sufficiently wide operational regime and may operate for 1,500 hours without any measurable degradation in performance.

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