Characterization of an adjustable magnetic field, low-power Hall Effect Thruster

IEPC-2011-143

Presented at the 32nd International Electric Propulsion Conference,
Wiesbaden • Germany
September 11 – 15, 2011

S. Oslyak[1], C. Ducci[2]
Research Engineer, Alta S.p.A., Pisa, 56014, Italy
P. Rossetti[3]
Project Manager, Alta S.p.A., Pisa, 56014, Italy
M. Andrenucci[4]
Professor, Aerospace Engineering Dep. University of Pisa,
CEO, Alta S.p.A., Pisa, 56014, Italy

Abstract: The effectiveness of the magnetic system based on permanent magnets is critically important in a Hall Effect Thruster (HET) because it determines its performance and lifetime capability. The right choice of the magnetic field topology and intensity, as well as solution of thermal problems relevant to low and medium power HETs, are crucial for the efficiency of the overall system.

This paper describes a first stage of the research work aimed at optimizing the magnetic system characteristics. It includes experimental results obtained on a laboratory model HT400 with nominal power 400 W and an adjustable set of permanent magnets enabling to vary the magnetic field intensities from 30 to 55 mT. Other features of HT400 are quasi-constant magnetic field topology within the wide range of obtainable magnetic field intensities and open axis-symmetric magnetic circuit, based on permanent magnets.

The magnetic system consists of several permanent magnets and two magnetic screens. It is build in such a way as to change the magnetic intensity in the channel by varying the number of magnets, but keeping the magnetic topology quasi-constant. The magnetic field intensity at the exit middle channel cross-section ranges in B_{rmax}=30,35,40,45,50,55 mT. Other feature of the system is the open magnetic circuit, i.e. all magnet surfaces are in contact only with non-magnetic materials. This allows to use highly thermo-conductive materials in direct contacts with magnets, keeping magnets in a relatively low temperature.

The feature allows thruster to operate in a wide range of power (250 W … 1.5 kW) and decrease total mass of the thruster.

Nomenclature

AMFR = Anode Mass Flow Rate;
CMFR = Cathode Mass Flow Rate;
V_d – discharge voltage;
I_d – discharge current;

I. Introduction

THE HT400 (**fig.1**) is a laboratory model of a Hall Effect Thrust designed to operate in low and medium ranges of power under varying intensities of the magnetic field. The model is being developed by Alta S.p.A as an internal project aimed to study the effects of magnetic field to performance of a

---

[1] Research Engineer, Alta S.p.A., PhD student, University of Pisa, Italy, s.oslyak@alta-space.com
[2] Research Engineer, Alta S.p.A., Italy, c.ducci@alta-space.com
[3] Project Manager, Alta S.p.A., Italy, p.rossetti@alta-space.com
[4] Professor, Aerospace Engineering Dep., University of Pisa, CEO, Alta SpA, Italy, m.andrenucci@alta-space.com

thruster. This paper is a part of the study and it is mainly concentrated on the results of performance analysis and technical features of the thruster with a fixed configuration of the magnetic field.

Low and medium power Hall Effect Thrusters (HETs) are a sub-class of Hall Thrusters with operating ranges 0.1..1.5 kW. This type of HETs can be installed onboard of a satellite for Telecommunication and Earth observation missions. In particular Low Power Hall Effect Thrusters (LP-HET) are significantly important for space missions with small satellites where power and mass budgets are strongly limited.

One of the most important components of a HET is a magnetic system (MS). Topology and intensity of a magnetic field in a HET determine performance and lifetime of a thruster. Currently there are two types of MS: MS based on magnetic coils and MS based on permanent magnets (PMs). Commonly MS based on magnetic coils consists of magnetic conductor circuit with several coils, number of magnetic screens, additional power supplier and magnetic field control system. Fundamental advantage of this MS is its flexibility to adjust topology and intensity of the magnetic field in a real-time, during thruster firing. This feature permits to achieve higher level of thrust under lower power consumption, which implies a rise of thrust efficiency. Topology and intensity of the magnetic field are adjusted and optimized by varying values of current in magnetic coils for each operation point of a HET. Main disadvantage of this MS is an addition power supplier necessary to supply coils. It implies the increase in overall mass of electric propulsion (EP) system and reduction of its reliability. The alternative is to use a single power supplier for coils and main plasma discharge but it reduces magnetic field flexibility and excludes the main advantage. Second disadvantage is sensitivity of such a MS to plasma oscillations in the channel of a HET. Oscillations of self-plasma fields induce oscillations of current in magnetic coils which require additional control devices.

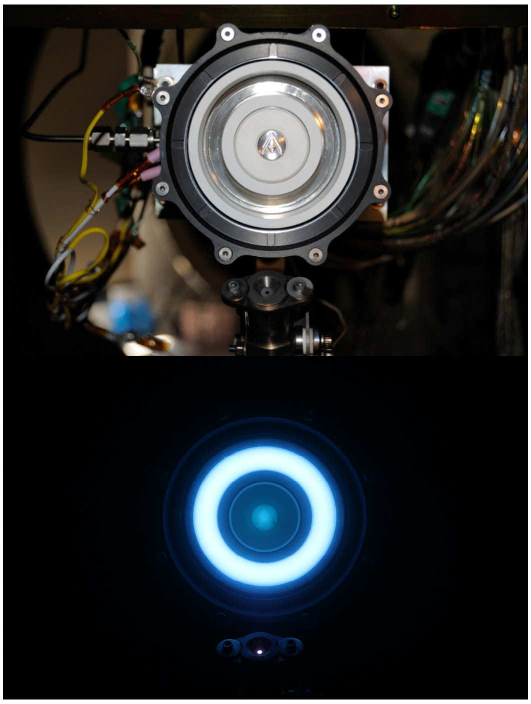


Fig. 1. HT400 on a thrust-stand

The advantage of MS based on permanent magnets is its simplicity. Commonly such a MS consists of magnetic conductor circuit based on a number of permanent magnets and magnetic screens. In contrast to a MS based on coils such a MS has lower mass and higher reliability due to the less number of components. This feature makes HETs with MS based on PMs significantly important for space missions with limited power and mass budgets. The main disadvantage of this MS is permanent topology and intensity of the magnetic field. In practice it eliminates an additional plasma tuning tool such as varying magnetic field. Therefore most of HETs with such a MS have reduced total thruster efficiency, lifetime and number of operating points. Next disadvantage of such a MS is difficult ignition of a thruster, in particular with high values of magnetic intensity.

The MS of presented thruster is based on permanent magnets and collects advantages of MS based on coils. According to obtained results this technique makes the thruster to operate on a high level of thrust efficiency, comparable with a thruster with adjustable magnetic field.

Main thruster parameters such as thrust, specific impulse and thruster efficiency are comparable with characteristics of a flight model, such as SPT-70.

II. Description and features of the thruster

Initially the HT400 had being projected to study the effects of magnetic field to thruster performance. Therefore the main structural feature of HT400 is capability to operate with both types of magnetic systems under varying intensities of the magnetic field. This feature permits to study performance of the thruster in a full range of magnetic field intensities typical for a HET (10..50, mT). The second feature is statically quasi-constant topology of the magnetic field in the channel for any values of magnetic intensity. It allows to separate influence of magnetic topology and intensity to the performance.

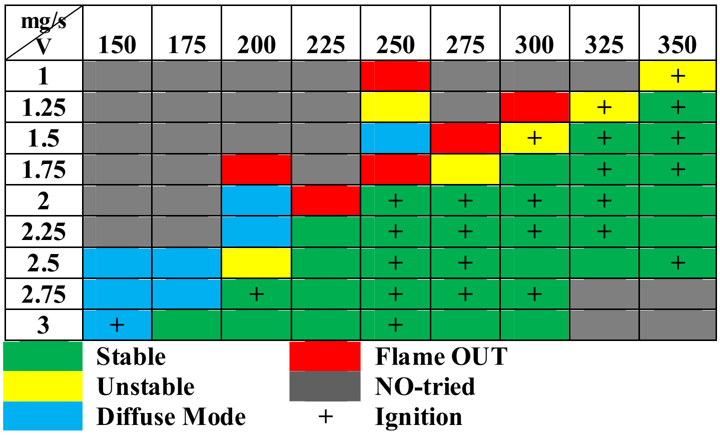
	HT400	SPT-70
Thrust, mN	9÷47	40
Power, W	160÷760	650
Specific Impulse, s	900÷1700	1450
Thrust efficiency	0.21:0.47	0.48
Lifetime, h	~3100	3100
Mass, kg	1.1	1.5
Ext. ceramics, mm	62	70
Magnetic field	PM	Coils

Table 1. Performance of the HT400 compared to the SPT-70

Magnetic system of presented modification of HT400 is based on two permanent magnets and has fixed topology and intensity of the magnetic field. The magnetic circuit of HT400 is open. In contrast to a closed circuit it has less weight and includes less number of parts. Open magnetic circuit allows to use a large spectrum of non-magnetic, high thermo-conductive materials for the frame of the thruster. It permits HT400 to operate in a large spectrum of power in a stationary mode, keeping magnets at a relatively low level of temperature.

The anode of HT400 has continuum labyrinth-surface distributor. In contrast to most of the anodes typical for HET it does not have holes for the gas injection. This feature allows to obtain uniform injection of the gas to the thruster channel.

Typical problem most of HETs with a magnetic system based on PM is the ignition of the discharge. Magnetic topology of the HT400 is designed in such a way that the thruster ignition is simple and stable in all operating range (see **Table 2).**



mg/s / V	150	175	200	225	250	275	300	325	350
1	⬛	⬛	⬛	⬛	🟥	⬛	⬛	⬛	🟨 +
1.25	⬛	⬛	⬛	⬛	🟨	⬛	🟥	🟨 +	🟩 +
1.5	⬛	⬛	⬛	⬛	🟦	🟥	🟨 +	🟩 +	🟩 +
1.75	⬛	⬛	🟥	⬛	🟥	🟨	🟩	🟩 +	🟩 +
2	⬛	⬛	🟦	🟥	🟩 +	🟩 +	🟩 +	🟩 +	🟩
2.25	⬛	⬛	🟦	🟩	🟩 +	🟩 +	🟩 +	🟩 +	🟩
2.5	🟦	🟦	🟨	🟩	🟩 +	🟩 +	🟩	🟩	🟩 +
2.75	🟦	🟦	🟩 +	🟩	🟩 +	🟩 +	🟩 +	⬛	⬛
3	🟦 +	🟩	🟩	🟩	🟩 +	🟩	🟩	⬛	⬛

🟩	**Stable**	🟥	**Flame OUT**
🟨	**Unstable**	⬛	**NO-tried**
🟦	**Diffuse Mode**	+	**Ignition**

Table 2. Map of operating points for HT400

III. Experimental Setup

All the test campaign was carried out in ALTA's IV4 test facility. A beam diagnostic rake equipped with Faraday cups was aligned with the center axis of the thruster in order to perform regular characterization of the plume. A PC based data acquisition was used to carry out regular data acquisition and storage at 1 Hz. General information about the test facility is presented in following sections. The detailed description was described in [5].

A. Vacuum facility

Alta's IV4 facility consisting of a main vessel (Auxiliary Chamber – AC), 2 m in diameter and 2.5 m in length connected through a 1 m gate valve to a service chamber (Small Chamber - SC), 1 m in diameter and 1 m in length. The two vessels are both built out of stainless steel AISI 316 L with low magnetic relative permeability (μ_r<1.06).

The main chamber provides the volume for expansion of the beam and contains the main pumping system, the beam target and the beam diagnostic devices. The SC is usually dedicated to the installation of the thruster, the thrust stand and all the connections (propellant, power lines, diagnostics) required for the thruster operation. However, for the present test, in order to improve the accuracy of the beam diagnostics, the thrust stand was placed in the AC and aligned with the Faraday cup rake's axis. At the far end of the AC, on the opposite side with respect to the thruster, a bi-conical, water cooled, Grafoil lined target is placed in order to dump the beam energy.

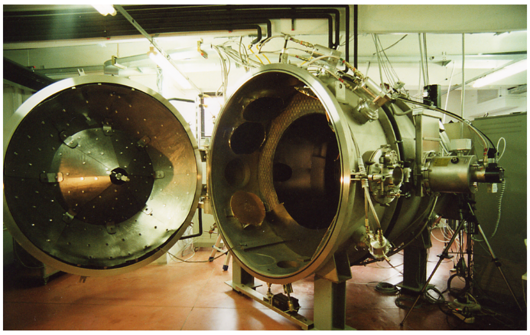


Fig. 2. IV4 vacuum facility's layout

B. Pumping system

The facility is equipped with two independent completely oil-free pumping systems: one connected to the AC and one connected to the SC for redundancy and emergency operations. The main pumping system includes, in addition to a 25 mc/hr rotary pump and a 2000 l/s turbomolecular pump used for evacuation, a cryogenic high vacuum stage based on 1 x 3000 l/s cryopump plus 6 x 12000 l/s custom cold plates. The total pumping speed is therefore in the order of 70000 l/s which ensured an ultimate vacuum <1e-7 mbar and a chamber pressure in the order of <2e-5 mbar (Xe) during the test campaign.

The pressure level within the chamber is continuously monitored by three Leybold-Inficon ITR90 Pirani/Bayard-Alpert sensors, two placed within the SC (i.e. behind the thruster) and one in the AC (nearly at the exit plane of the thrusters). A SRS RGA-200 is placed in the SC to monitor the composition of the residual background gas. Usually all the partial pressures of gases (except Xe) are <1e-7 mbar during thruster operation.

C. Cathode

K&R cathode was used as the neutralizer. Main characteristics of the cathode are presented in the **Table 3**.

This model of cathode is not optimized for space applications (e.g. there is not thermal shield) and it was not optimized for the current thruster. In particular, the operating level of CMFR is 3÷4 times higher than it is necessary for a stabile operation of HT400. Excess of propellant injected by the cathode near by thruster's exit cross-section had impaired plume characteristics.

Parameter	Value
Discharge Current, *A*	1÷4
Max Discharge Current, *A*	10
Ignition tension, *V*	600
Xe MFR, *mg/s*	0.9÷3
Mass, *g*	200

Table 3. K&R cathode: main technical specifications

IV. Test results

Currently the overall map of operating points is not complete. In particular, the thruster was tested on a partial load mode with maximum power level about 750 W and upper limit of accelerating voltage ~350 V. In fact, it is only a 50% from maximum power level on which the thruster can operate in continuous mode.

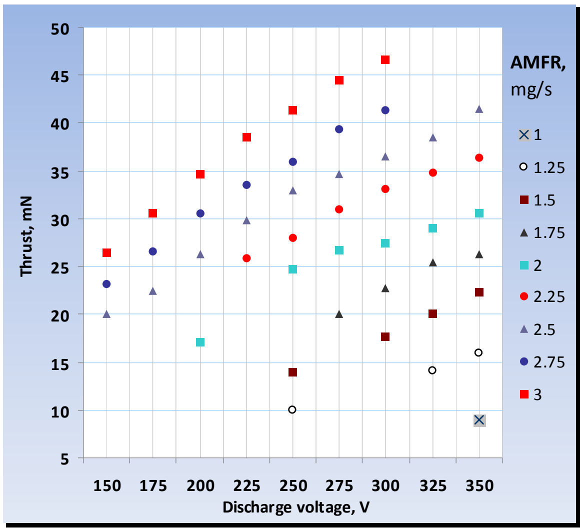


Fig.3 Measured thrust as a function of the discharge voltage under varying anode mass flow rate.

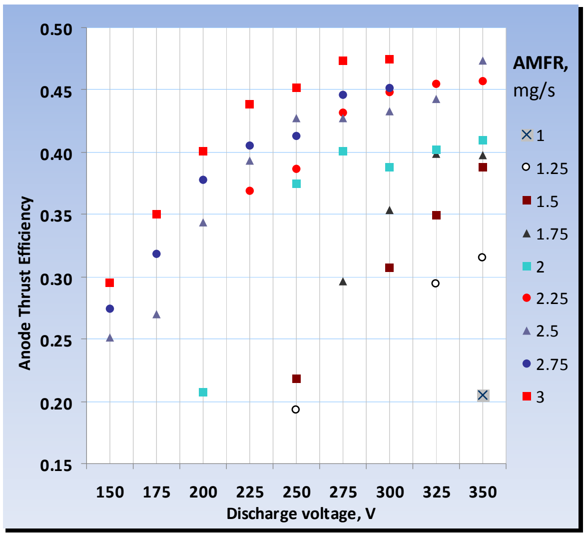


Fig.4 Thrust efficiency as a function of the discharge voltage under varying anode mass flow rate.

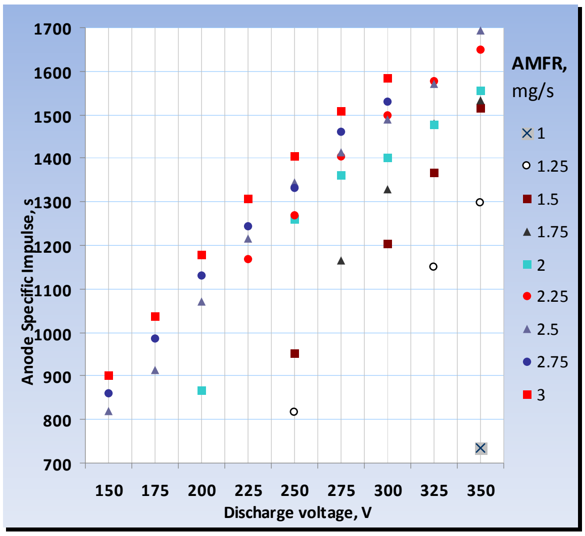


Fig.5 Specific impulse as a function of the discharge voltage under varying anode mass flow rate.

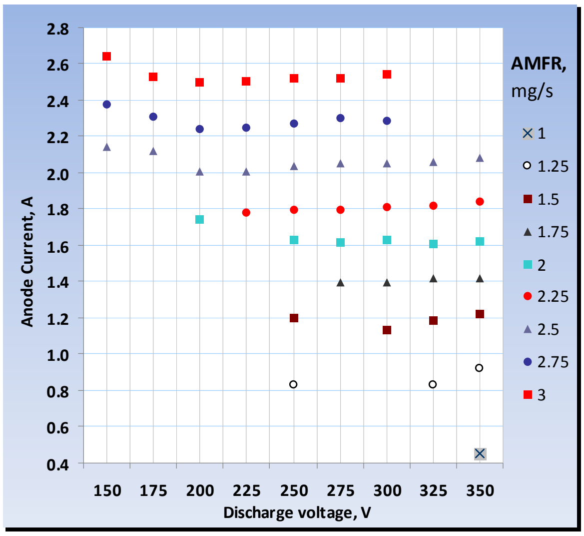


Fig.6 Measured discharge current as a function of the discharge voltage under varying anode mass flow rate.

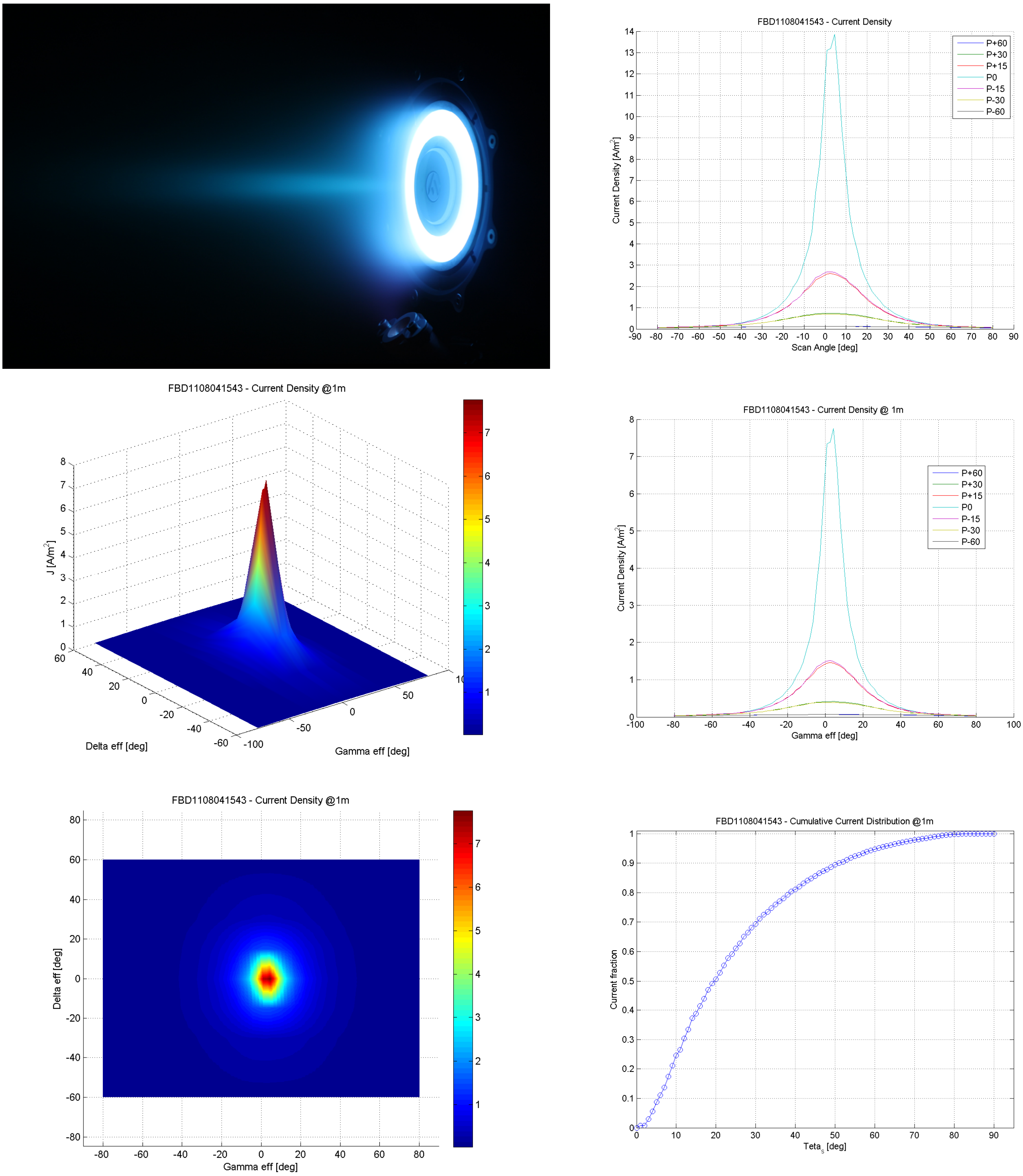


Fig. 7. HT400 during firing and corresponding plume characteristics; *Operating mode:* V_d*=375 [V];* I_d*=2.1 [A], AMFR=2.5 [mg/s], CMFR=1.1 [mg/s],* I_{beam}/I_d*=79.64%, beam divergence 60.01°;*

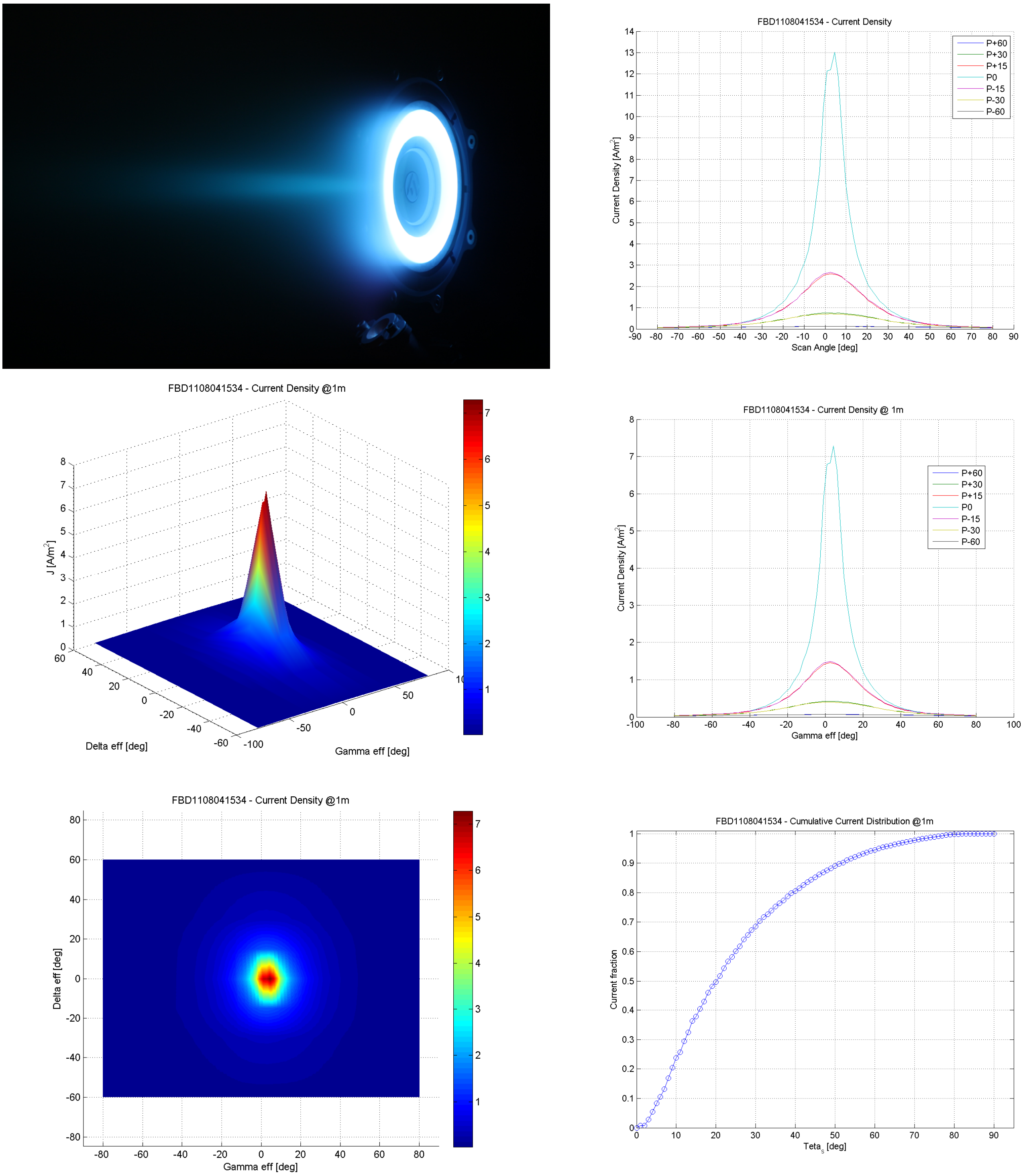


Fig. 8. HT400 during firing and corresponding plume characteristics; *Operating mode: V_d=350 [V]; I_d=2.1 [A], AMFR=2.5 [mg/s], CMFR=1.1 [mg/s], I_{beam}/I_d=79.13%, beam divergence 60.01°;*

V. Conclusion

The test campaign carried out on the HT400 thruster allowed the experimental characterization (including direct thrust measurements) of its performance in a wide range of discharge voltages and anode mass flow rates.

Stable operation and stable characteristics of the discharge (current and voltage) were evidenced in all the operating range. The discharge ignited stably and constantly at every test point under large range of discharge voltages and AMFRs even near by the area of the discharge instabilities (**Table 2**).

Future activities on HT400 will focus on the optimization of the cathode (model, position etc.) to improve the plume characteristics, on a performance characterization using larger range of discharge voltages and AMFRs, studying the thruster in higher thermal-stress mode near by the theoretical limit. The study of thruster's performance under varying values of magnetic field intensities will be continued basing on the results obtained on HT400.

Acknowledgments

The authors wish to thank Mr. Massimo D'Urso for several technical solutions applied in HT400 and for splendid technical realization of engineering ideas of the authors.

References

Periodicals

[1] A.I. Morozov, V.V. Saveluev Onedimensional '*Hybrid Model of Plasma Thruster*', Plasma Physics Reports, Vol. 26, No. 10, 2000, 880

[2] V. Kim, '*Main Physical Features Processes Determining the Performance Stationary Plasma Thrusters*', Prop. and Power, Vol. 14, No. September-October, 1998.

Books

[3] N.V. Belan, V.P. Kim, A.I. Oransky, Tihonov in: 'Stationary Plasma Thrusters' pp. 151-159, (in Russian) Kharkov, 1989

[4] A.I. Morozov, V.V. Saveluev 'Fundamentals of Sationary Thruster Theory'

Proceedings

[5] M. Saverdi, M. Signori, and L. Biagioni 'Experimental characterization of the HT-100 Hall thruster in twin engine cluster configuration', *30th International Electric Propulsion Conference,* Italy 2007

[6] M. Andrenucci, F. Paganucci 'Fundamental laws for the electric propulsion concepts'

[7] M.B.Belikov, O.A.Gorshkov, V.A.Muravlev, R.N.Rizakhanov, A.A.Shagayda, A.U.Shnirev, "High Performance Low Power Hall Thruster", AIAA-2001-3780, *37th JPC, July 2001, Salt Lake City,USA*