H2020 MINOTOR: Magnetic Nozzle Electron Cyclotron Resonance Thruster

IEPC-2019-875

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

D. Packan[1], P.Q. Elias, J. Jarrige, T. Vialis, S. Correyero, S. Peterschmitt, J.-C. Porto-Hernandez
ONERA, Palaiseau 91120, France

M. Merino[2], A. Sánchez-Villar, E. Ahedo
UNIVERSIDAD CARLOS III DE MADRID (UC3M), Leganes 28911, Spain

G. Peyresoubes[3], A. Thorinius, S. Denis
THALES MICROELECTRONICS (TMI), Etrelles 35370, France

K. Holste[4], P. Klar, S. Scharmann, J. Zorn
JUSTUS-LIEBIG-UNIVERSITAET GIESSEN (JLU), Giessen 35390, Germany

M. Bekemans[5], T. Scalais, E. Bourguignon
THALES ALENIA SPACE BELGIUM (TAS-B), Mont sur Marchienne 6032, Belgium

S. Zurbach[6], P. Azais, I. Habbassi
SAFRAN AIRCRAFT ENGINE (SAFRAN), Paris 75015, France

and

M. Mares[7], A. Hoque
L – UP (LUP), Paris 75008, France

Abstract: Electric propulsion has been identified by European actors as a strategic technology for improving competitiveness in different space areas such as in-space operations and transportation. The European Commission has set up the "In-space Electrical Propulsion and Station-Keeping" Strategic Research Cluster (SRC) in the "Horizon 2020" funding framework with the goal of enabling major advances in Electric Propulsion for in-space operations and transportation. In this framework, the MINOTOR project was funded to mature a potentially disruptive cathodeless electric propulsion technology, the Electron Cyclotron Resonance (ECR) thruster. In recent years, the consortium leader ONERA has built up a large experience on ECR technology for electric propulsion, and the MINOTOR project will bring the expertise from three industrial partners (TMI, TAS-B and SAFRAN) and two university partners (UC3M and JLU) to take the next step.

[1] Project coordinator, research scientist, denis.packan@onera.fr
[2] Assistant professor, mario.merino@uc3m.es
[3] Technical director, georges.peyresoubes@fr.thalesgroup.com
[4] Senior Scientist, Kristof.Holste@exp1.physik.uni-giessen.de
[5] Head of R&I, marc.bekemans@thalesaleniaspace.com
[6] Research scientist, stephan.zurbach@safrangroup.com
[7] Consultant, magali.mares@l-up.com

List of Abbreviations

ECR	Electron Cyclotron Resonance
ECRA	Electron Cyclotron Resonance Acceleration
EPIC	Electric Propulsion Innovation and Competitiveness
GIE	Gridded Ion Engine
HET	Hall Effect thruster
HEMP	High Efficiency Multistage Plasma Thruster
HPT	Helicon Plasma Thrusters
H2020	Horizon 2020
ICR	Ion cyclotron Resonance
LIF	Laser Induced Fluorescence
MPD	Magneto Plasma-Dynamic thruster
MW	Microwave
NSSK	North-South Station Keeping
PIT	Pulsed Inductive Thruster
PIC	Particle In Cell
PPT	Pulsed Plasma Thruster
PPU	Power Processing Unit
SRC	Strategic Research Cluster
SURFET	SimUlator for RF Electrodeless Thrusters

I. Introduction

The **MINOTOR** project (**M**agnet**I**c **NO**zzle elec**T**ron cycl**O**tron **R**esonance thruster) was selected for funding in the H2020 call RIA H2020-COMPET-3-2016-b "SRC - In-Space electrical propulsion and station keeping - Disruptive Technologies", which goal is to provide maturation of low TRL technologies. The SRC is called EPIC (Electric Propulsion Innovation and Competitiveness - http://epic-src.eu/) and is managed by ESA.

MINOTOR's objective is to demonstrate the feasibility of the ECRA technology (Electron Cyclotron Resonance Accelerator) as a disruptive technology for electric propulsion, and to prepare roadmaps for the potential future developments of the technology. The project is focused on the understanding of the physics and the demonstration of the technology, rather than on the production of a fully operational prototype.

Based on electron cyclotron resonance (ECR) as the sole ionization and acceleration process, ECRA is a cathodeless thruster with magnetic nozzle, allowing thrust vectoring. It has significant potential advantages in terms of global system cost and reliability compared to mature technologies. It is also scalable and can potentially be considered for all electric propulsion applications.

The plasma is created by ECR inside the thruster cavity by injecting and ionizing neutral gas, resulting in a high-density plasma. The topology of the external magnetic field is purely diverging and acts as a magnetic nozzle, where the magnetized electrons are accelerated by the conservation of the electron energy and magnetic moment μ. This leads to an ambipolar electric field that directly accelerates ions to high velocities. Electrons with high energy escape the potential barrier to conserve the quasi-neutrality of the exhaust plasma beam, which is ensured since the thruster is floating. Thus, neither grids nor hollow cathode neutralizers is not needed. The plasma then detaches from the magnetic lines and produces a net thrust force.

The project is based on an experienced consortium of 7 partners from 4 countries (Table 1). The duration of the project is 3 years, starting in January 2017, with ONERA as coordinator.

Based on the first preliminary results [1-7], the project studied the physics both experimentally and numerically, and along the impact on the PPU. This led to numerous conference and journal publications [8-32], and significant achievement in all work packages.

The complexity of the physics at play has been an obstacle for the understanding and development of the technology. Indeed, the ionization chamber involves absorption of microwave energy in a magnetized, flowing plasma, which is challenging to model, and the understanding of the physics in the magnetic nozzle is still a subject of research. Thus, an in-depth numerical and experimental investigation plan has been devised for the project, in order to bring the ECRA technology from TRL3 to TRL4, the current level of the thruster system.

Participant no.	Participant organisation name	Participant short name	Country
1 (CO)	Office National d'Etudes et de Recherches Aérospatiales	ONERA	France
2	Universidad Carlos III de Madrid	UC3M	Spain
3	Thales Microelectronics SAS	TMI	France
4	Justus-Liebig-Universitaet Giessen	JLU	Germany
5	Thales Alenia Space Belgium SA	TAS-B	Belgium
6	Safran Aircraft Engines	SAFRAN	France
7	L-UP SAS	LUP	France

Table 1. Composition of the MINOTOR consortium.

II. Objectives of MINOTOR

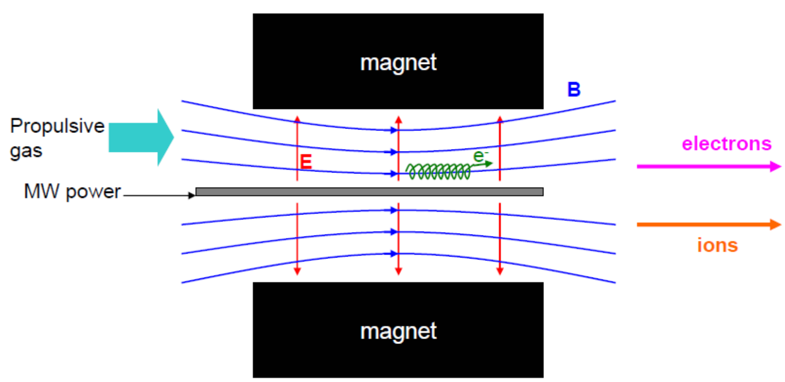
The objectives pursued are:

- Get a full understanding of the physics, by in-depth numerical modelling studies in parallel to an extensive experimental investigation, leading to optimised designs, performance maps and scaling laws for the thruster;
- demonstrate ECRA performances with tests at three thrust levels (30W, 200W and 1 kW) and erosion tests;
- demonstrate features such as compatibility with alternative propellants and magnetic beam steering;
- demonstrate the feasibility of an efficient PPU;
- determine quantitatively the impact of the ECRA technology on the EP system and satellite platform at systems level, and establish the future industrial roadmaps for development. These roadmaps shall aim at realising a high TRL in the timeframe of 2023-2024.

III. Description and advantages of the technology

A. Introduction

Electric propulsion for satellites has become widespread, with the use of mostly two technologies: gridded ion thrusters (GIE) and Hall Effect thrusters (HET). Both fall in the category of electrostatic thrusters: a static, applied electric field (high voltage 300- 2000 V) accelerates ions which provide the thrust. In order to avoid satellite charging, neutralization of the beam is done with an electron source (the neutralizer). Few, if any, other high I_{sp} (>1000 s) electric thrusters are used on satellites. And few studies are devoted to the development of other thrusters, due to the difficulty of experimental work and of the physics involved.



In the course of plasma sources development, new configurations of ECR thrusters were tested at ONERA. ECR thrusters are based on the principle of plasma acceleration by a magnetic nozzle without the use of electrodes.

The principle is exposed on Figure 1. The plasma is efficiently created by the physical process called Electron Cyclotron Resonance and is accelerated by the diverging magnetic field. Although the principle of this thruster is not new, the configuration used (with a central antenna) and size (small compared to the wavelength) is proprietary to ONERA. A patent has been obtained on this thruster design by ONERA (reference FR 2985292).

B. Physics of the thruster

Let us start with an unmagnetized plasma. When a plasma is created in an open cavity (a thruster), some outward acceleration of the plasma occurs, called ambipolar acceleration: the mere pressure of the electron gas (which is much larger than that of the ions due to their much higher temperature) will "blow" the whole plasma out of the thruster. Indeed, since the plasma is usually quite dense in a thruster (>10^{12} cm^{-3}) the electrostatic forces will keep the electrons and ions together (quasi-neutral behaviour), i.e. the ions will be forced to follow the electrons. It means that the exiting plasma is overall neutral, i.e. as many ions as electrons flow out.

ECRA has a longitudinal static magnetic field applied, which brings the following further properties:

1. **Ionization performance:** In the direction perpendicular to the magnetic field (~radial direction), the electrons are somewhat trapped around the field lines and perform circular trajectories at a frequency that is independent of their energy, and only dependent on the magnetic field strength. It is the cyclotron frequency $\omega = \frac{e.B}{m_e}$. If the magnetic field and microwave frequency are properly tuned, the AC electric field is in phase with the rotating electrons, and keeps energizing them as long as they stay in the resonance region. In this resonance process, called Electron Cyclotron Resonance (ECR) the electrons will acquire very high energies, which will make them ideally suited for ionizing the incoming flow of neutral gas that is fed in the thruster.

2. **Efficiency and lifetime:** The longitudinal magnetic field lines trap the electrons as explained previously. Hence, the ions will also be trapped by the magnetic field line since they are electrostatically tied to the electrons, and will not diffuse toward and impact the thruster walls (in the reality diffusion still occurs but at a lower rate). Fast diffusion to the walls is usually not only related to energy loss, but also to sputtering of the wall leading do decreased performances and lower lifetime. Hence, the natural magnetic shielding (845 gauss) of the ECRA thruster leads to efficiency and lifetime advantages.

3. **Plasma acceleration:** Since the plasma is "blown out" by the electron pressure, the high electron temperature in an ECR thruster (measure up to 40-60 eV) will lead to a high electron pressure and thus a high plasma velocity. But there is more. First, we should note that the energy that is used for the electron pressure to blow out the plasma is mostly the longitudinal kinetic energy. The "lateral" kinetic energy of the electrons (which is 2/3 of its energy in an isotropic plasma) is not used. But in the presence of the magnetic field, where the "lateral" movement of the electron is a circle, this lateral movement will be transformed into a longitudinal movement due to the magnetic field gradient: this is the "$\mu \cdot \nabla B$" force, where μ is the magnetic moment of the electron due to its circular movement. This is the magnetic nozzle effect: the "side" pressure transforms into a forward pressure. These two effects (higher electron temperature and $\mu \cdot \nabla B$ conversion) make the acceleration much higher than without magnetic field. And indeed, in ECRA, ion energies up to 400 eV have been observed, which is a relevant energy level for a thruster.

The process of the beam leaving the magnetic nozzle is called "detachment". Indeed, the electrons (and thus the plasma) are initially tied to the magnetic field lines, but when the ions (which are not magnetized, i.e. they do not "see" the magnetic field) gain enough longitudinal momentum from the DC ambipolar field acceleration, they "pull" the electrons with them and the plasma beam detaches. This process is currently the subject of research works in order to be modelled correctly.

C. Relations with other thruster technologies

The physics of ECRA can be categorized in comparison to other technologies of electric propulsion. A classification of the technologies by acceleration process is illustrated in Table 2. Note that the classification relates to the acceleration process because this is where the vast majority of the power goes in a thruster. Indeed, the ionization process (if any) may be different from the acceleration process in some technologies, such as GIE (where the ionizing discharge may be DC, RF or MW) and ICR "VASIMR" (where the ionizing discharge is helicon). The last three columns concern thruster with both an electric and a magnetic field, and these fields are usually perpendicular with the three possible orientations illustrated and utilized by different thruster technologies.

ECRA has the closest physical ties with the thrusters on the last column ("magnetic nozzle" column) of Table 2: HPT and ICR.

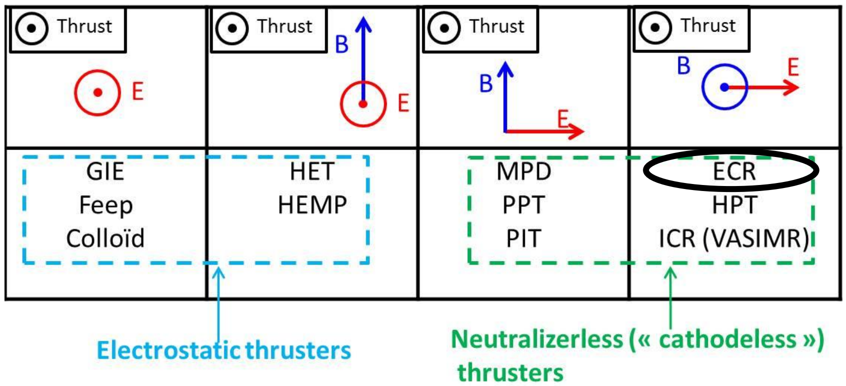


Table2: Categorizing of thrusters depending on the acceleration principle. ECRA is an ECR thruster (circled)

D. Advantages of the technology

The ECRA thruster is a cathodeless thruster with magnetic shielding and magnetic beam steering. It is composed of an ECR ionization chamber and a magnetic nozzle. Its intrinsic traits are that it requires only a single electrical input (microwave), a single gas feed system (for the main thruster chamber), and does not need neutralizer nor grids. The potential advantages are:

- Lower recurring cost;
- Higher reliability;
- Longer lifetime;
- Magnetic thrust vectoring;
- Complete compatibility with all propellants, including oxygen (advantages for air breathing applications, alternative propellants);
- Possibly: variable Isp and high efficiency.

The potential advantages of the ECRA thruster compared to current mature technologies are summarized in Table 3. The design is scalable to low and large thrust by increasing the size of the thruster area. It is particularly striking that the expected lower recurring cost of the technology concerns virtually all the elements in the thruster system: the thruster, the vectoring system, the propellant, the fluidic line, the tank and the PPU.

At the current level of development (TRL 3), there are obviously many questions remaining, such as whether it can achieve both a reasonable lifetime and practical efficiencies, or whether the cost advantage on the PPU architecture are not offset by the cost of the microwave generator needed. Experimental investigations are ongoing, and the physics understanding of the thruster is far from complete. But the simplicity of the thruster and the promising results already obtained warrant in depth studies.

Characteristics	System impact	Advantage
No Neutralizer	Removal of the neutralizer as a critical component (failure, lifetime)	Lower recurring cost Higher reliability Longer lifetime
	Simplified PPU	
	Single fluidic line	
	Low Xe purity acceptable	
	Reacting gases acceptable (e.g. O_2)	
No fragile or complex parts, low part number	Simple design, no grids	
Magnetic nozzle	Thrust vectoring	
	Ambipolar acceleration	
	Magnetic shielding	
Microwave power = only electrical input	Simplified PPU	
	DC uncoupling of thruster and PPU	
	Low voltage components	
	No flow controller needed (open loop)	
	MW generator = new element in PPU	Cost addition

Table3: Main advantages of the ECRA thruster compared to current mature technologies.

E. Challenges for the study

There are experimental and numerical difficulties in studying and developing ECRA, which in part explain why this concept has not been investigated in depth in the past.

1. Experimental challenges

The determination of the main characteristics of the thruster is challenging, and need a particular attention to the experimental setup, for three main reasons.

a) With the dominant technologies HET, GIE or HEMP, which all belong to the class of electrostatic thrusters, a DC supply is used to power the acceleration process. Thus, within say 20%, the voltage supplied gives approximately the ion energy, and the current supplied gives approximately the beam current, and hence the ionization fraction (from the gas mass flow rate). These are already extremely useful information to estimate the beam and thruster properties. With ECRA, the power supply only gives the MW power, and one does not know, for example, whether the ion energy is 10 eV or 400 eV, and whether the ionization fraction is 0.1% or 80% (assuming the power input allow all these numbers). Nearly all the characteristics of the thruster performance, even at first order, have to be measured in vacuum, including with calibrated probes for detailed efficiencies.

b) A particularly good vacuum is also necessary for the actual operation of magnetic nozzle thrusters. Indeed, the magnetic nozzle can be considered as an extension of the ionization chamber, and extends well inside the vacuum chamber. A high background pressure has been shown to lead to considerably lower thruster performances. Typically, it is considered that ECRA needs a pressure of less than 10^{-5} mbar to work properly, which is in contrast with HET for example, that can be fired in vacuum levels up to 10^{-4} mbar safely.

2. Numerical modelling challenges

ECRA offers a particular combination of physics modelling difficulties, such as coupled acceleration and ionization zones, and wave propagation processes. This is illustrated in Table 5, where different technologies are classified depending on their physics. Thus, an enhanced effort must be spent on the modelling and the MINOTOR project has integrated this challenge.

		FREQUENCY			
		DC	**MHz or pulsed µs (λ>L)**	**GHz (λ<L)**	
IONIZATION AND ACCELERATION ZONES	**Separated**	GIE	ICR-VASIMR		↓
	Coupled	HET HEMP MPD	HPT PPT PIT	**ECRA**	
Growing modeling difficulty		→			

Table4: EP technologies classified depending on their physics and difficulty of modeling

F. State of the art

The experimental configuration typically used for ECRA is shown in Figure 2. The inner diameter of the thruster (the ionization chamber) was test up to 27 mm.

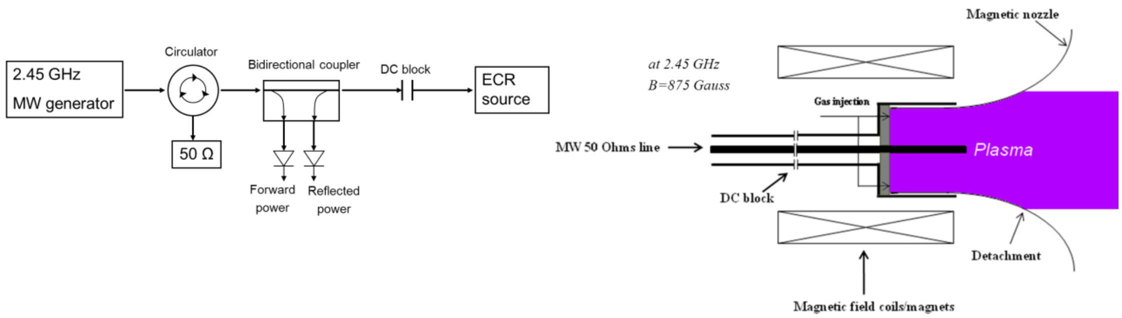


Figure 2: Typical microwave circuit used (left) and thruster configuration (right)

Preliminary designs were developed (Figure 3).

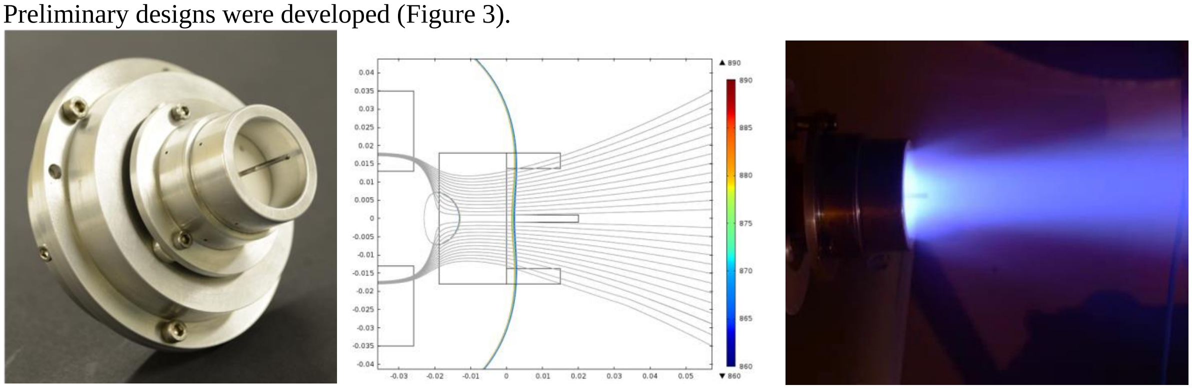


Figure 3: Magnet version of ECRA (left) and plume observed at ONERA (right)

The state-of-the-art performance of ECRA is presented in Table 6.

Gas	Mass flow rate [mg/s]	Power absorbed [W]	ion energy [eV]	Ion current [mA]	Thrust [mN]	Thrust to Power ratio [mN/kW]	Isp [s]	Mass utilization efficiency [%]	Power efficiency [%]	Divergence efficiency [%]	Thruster efficiency [%]
Xenon	0,1	30,0	248,5	45,5	0,98	33	1001	0,62	0,38	0,83	16,1%

Table 1: Current state-of-the-art of the performance obtained with the ECRA thruster

A total efficiency of about 16% is obtained at a 30 W power level and about 1 mN thrust level. Ion energy is about 250 eV. This level of performance is actually on par or higher than other technologies at that thrust level, although comparison is difficult as few mature technologies have been developed and fully characterized at that power level. And for plasma thrusters, efficiency always increases with size and power, because of lower diffusion losses, thus ECRA seem a promising technology, and ideally a goal would be to reach 50% efficiency or higher at the 1 kW power level.

IV. Organization of the consortium

The organization of the technical work-packages of the MINOTOR project is shown in Figure 4.

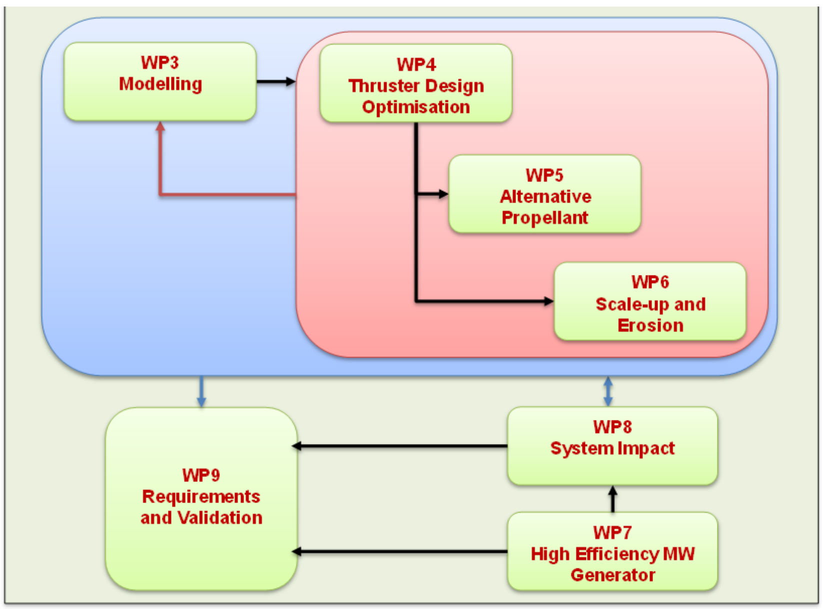


Figure 4. Technical work-package organization of the MINOTOR project.

Although several parameters will be used to measure and characterize the performance of ECRA in the course of the project, the main figure of merit for the performance will be the total efficiency of the thruster. Indeed, if the efficiency of a thruster is lowered, it usually implies lower thrust, more difficult thermal management, more gas consumption and lower lifetime.

The main achievements so far are briefly described below:

A. Numerical modelling

Two codes are developed and are being used in MINOTOR. The main code is the hybrid code SURFET, developed by UC3M, and should allow simulation of a large part of the thruster. The PIC code ROSEPIC, developed by ONERA, will be used to model specific ares or working points.

1. SURFET

The main code to be used in the course of the project is the SURFET code from UC3M. SURFET consists of 4 separate modules, each tailored to one part or process of the ECRA. After two years of development, they have been recently merged into a single code to be used for simulations of the thruster. The four modules are described in Table 2. More details can be found in [27].

Plasma-wave interaction module	• 2D divergence-free Finite Elements with PML boundary conditions • Cold plasma dielectric tensor (away from resonances) • Auxiliary 1D kinetic code for electron response and heating in resonance regions
PIC sub-code	• 2D PIC code for ions and neutrals • DSMC collisions solver
Electron sub-code	• 2D advanced anisotropic fluid model • Quasi-structured magnetic mesh
Magnetic nozzle module	• Two-fluid ion-electron quasi-neutral code • Magnetized electrons • Self-consistent plasma-induced magnetic field • Collisions, anisotropy, collisionless cooling mechanisms

Table 2. Description of the modules of SURFET

Preliminary simulations of the thruster are presented in Figure 4.

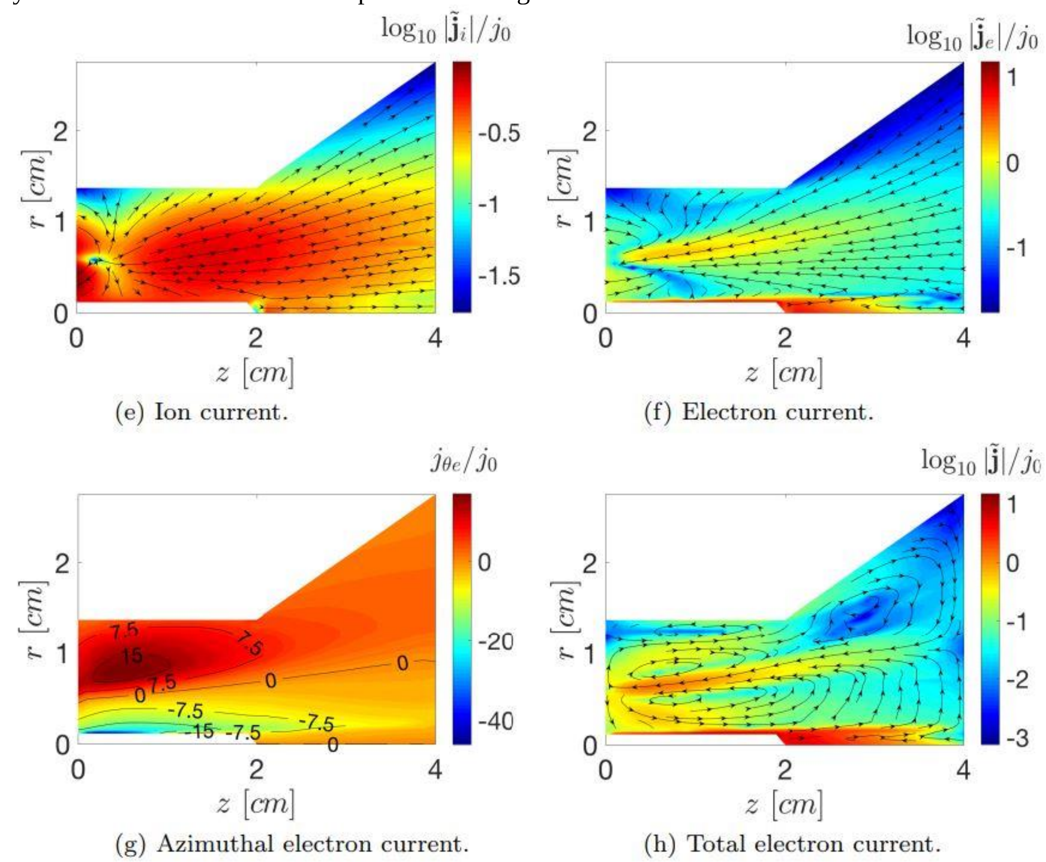


Figure 5. Preliminary simulation of the ECR thruster with SURFET: the cylindrical part is the thruster, and the conical part is the calculation domain of the magnetic nozzle.

2. ROSEPIC

The 3D electromagnetic Particle-In-Cell/Monte-Carlo Collision (PIC/MCC) method is a tool of choice to deal with the challenges of EP. Up to now the complete simulation of an electric thruster has been out of reach of full PIC models, due to insufficient computational power. But the emerging massively parallel computing platforms give a more widespread access to Teraflops-sized clusters at ever-decreasing costs (ex. Intel Xeon Phi, GPGPU). ROSEPIC will be able to simulate complex aspects of the thruster physics, up to a full thruster, in order to explain the physical processes of importance. The model of these physical processes can then be included into the faster SURFET code.

ROSEPIC	Status	Improvements to come
Geometry	1D, 2D, 3D	
Mesh	Block-refined meshes	Local mesh Refinement
Parallelism level	Hybrid: MPI + OpenMP	3-level parallelism: MPI + OpenMP + GPU
Particle Pusher	Explicit	Guiding center
Field Solver	Electrostatic Approximate Maxwell (Darwin)	Full Maxwell (FDTD)
Particle Boundary Conditions	Source / Sink on static surfaces	Erosion source
Field Boundary conditions	Fixed / Floating potential, surface charge on imbedded dielectric	Perfectly Matched layers

Table 3. Characteristics of ROSEPIC.

First results based on a reducd 1D-3V module are shown in Figure 6. The 2D simulations of ROSEPIC will be performed soon.

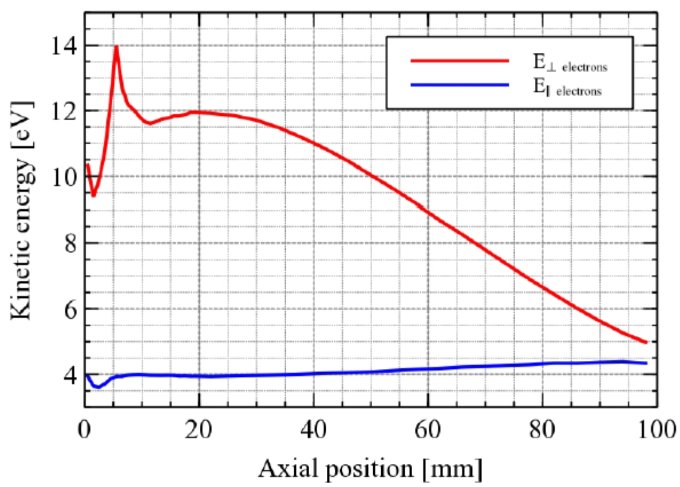


Figure 6. 1D-3V full PIC simulations of the magnetic nozzle of an ECR thruster, showing the cooling of the perpendicular energy and convergence of the energies in the two modes.

B. Experimental thruster design tests

This work package is composed of experimental investigations of different thruster design, configurations and parameters. Many achievements have been obtained:

- Confirmation if the acceleration zone of the thruster (LIF + Langmuir)
- Direct measurement of separate pressure and magnetic thrust (thrust balance)
- Measurement of plasma diamagnetism and Te perpendicular
- Optimisation of the thruster microwave coupling
- First test of the waveguide thruster and further manufacturing
- Evidence of impacts on antenna and first test of boron nitride coating
- Evidence of plasma beam confinement (backplate impact)
- Test of different gas injection strategies
- Confirmation of thruster performances and of background pressure effect at the Jumbo facility (JLU)

To illustrate the efforts, two campaign results are shown below.

The waveguide thruster is illustrated in Figure 7. Measurements are ongoing, and the efforts have been on the choice of the ceramic materials and on the microwave coupling, which is much different than with the antenna thruster.

Figure 7. Picture of the waveguide thruster (left) and its plasma (right).

The ECR coaxial thruster was tested at the large Jumbo facility in Giessen, and the results were compared to those taken at ONERA (Figure 8). The results obtained in Jumbo were better, due to the better vacuum. The reason for the effect of vacuum level are still under investigation, but have been well characterized.

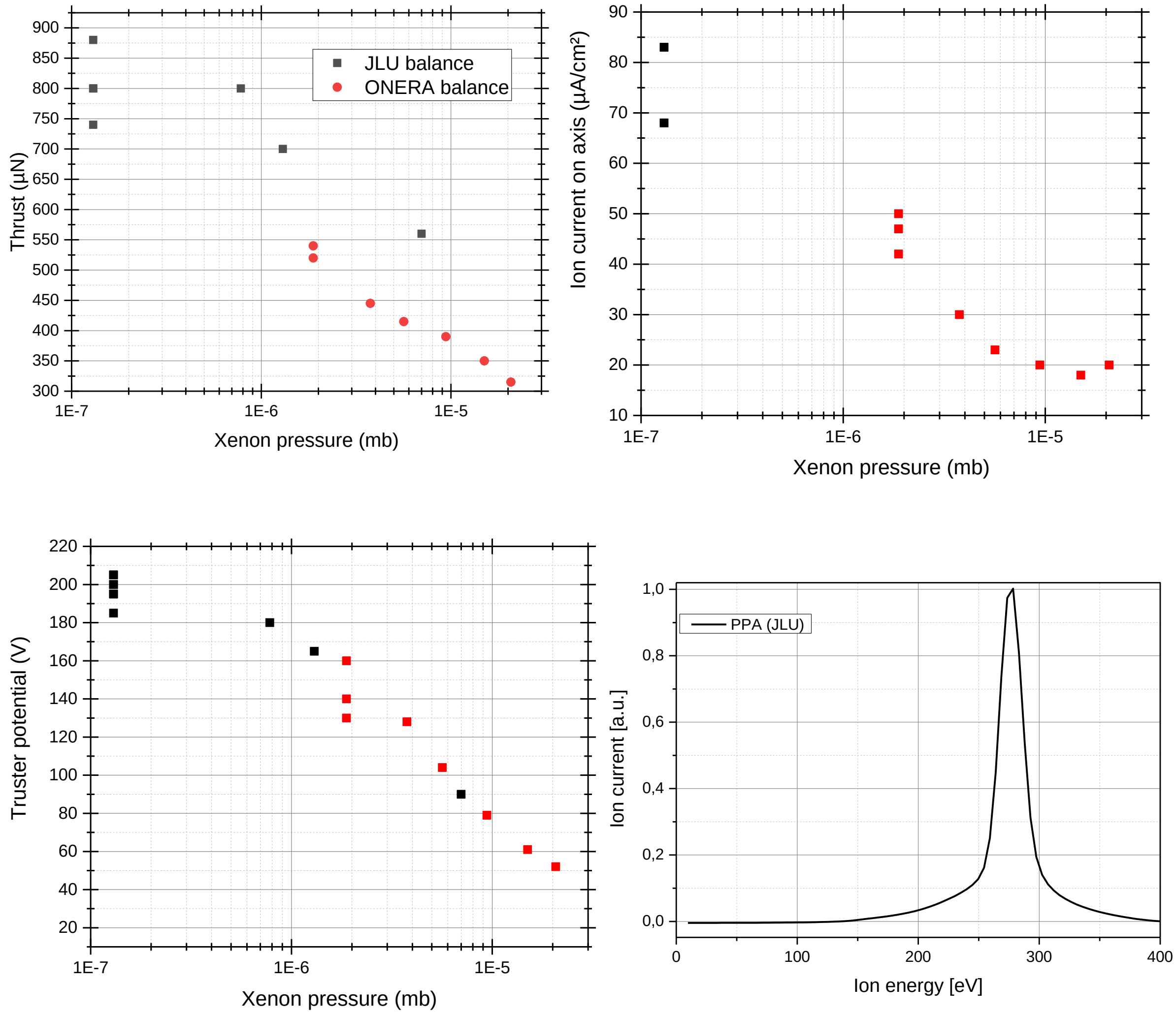


Figure 8. Picture of the ECR thruster in the Jumbo facility at JLU (top) and comparison of performance measurement at JLU (black dots) and at ONERA (red dots).

C. Scale-up and erosion

Scale-up tests are considered at two power levels, 200W and 1 kW, in order to test a large range of thrust levels in a progressive way. The actual optimized thruster scale-ups is still being studied, and experiments will be conducted at the large JUMBO vacuum facility at JLU in Giessen. JLU has developed a specific thrust balance for the tests.

D. High efficiency microwave generator

The goal is to demonstrate than a high efficiency (>80%) MW generator can be conceived, in order to be integrated into and ECRA PPU in the future. The development of the microwave generator is based on the following preliminary requirement specifications:

- Input: DC 48 Volt;
- Frequency: 2.45 GHZ +- 200 MHz;
- Output impedance: 50 ohm.

TMI has developed the proper technology, and a first breadboard has been tested at 5W (Figure 9). A 25W tests is coming soon. These results show that the microwave generator is not a show-stopper for the technology.

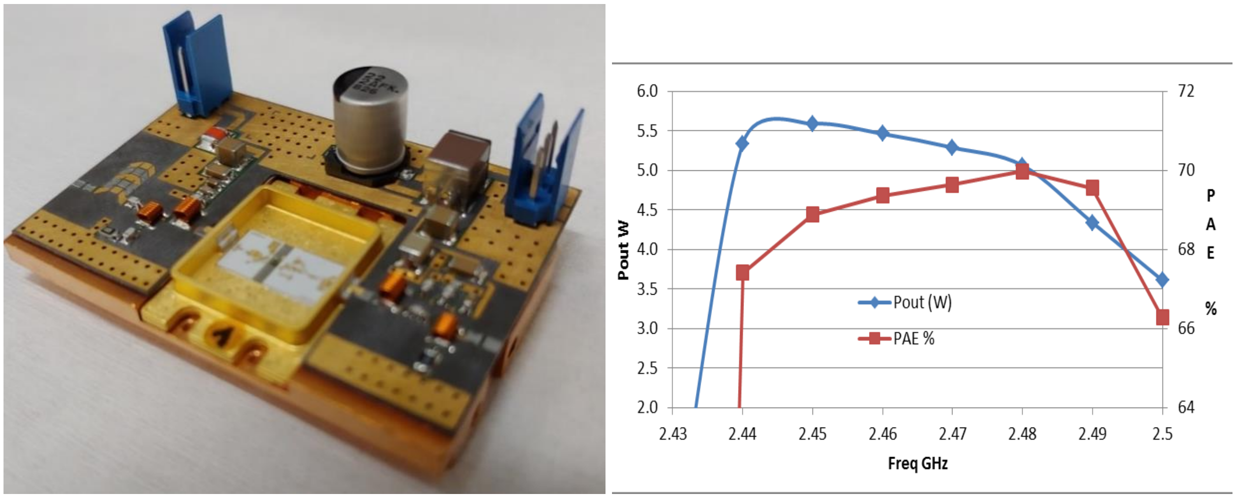


Figure 9. 5W amplifier and matching networks (input and output ceramics) : dimension 5 cm, weight 100 gr, efficiency >70%. Improved performances are expected at 25W.

E. WP8: System impact

Several positive system impacts of the ECR technology have been identified and concern:

- The PPU;
- The thruster system, including the fluidic system, TOM and platform aspects.

In particular, the PPU impact has been studied by TAS-B, given that no cathode, no galvanic isolation and only one gas line is required. A reduction of cost (microwave generator apart) of more than 50% is expected. For small plateforms where the bus voltage matches the microwave amplifier input, direct drive is possible and the cost can be reduced by 90% (Figure 10).

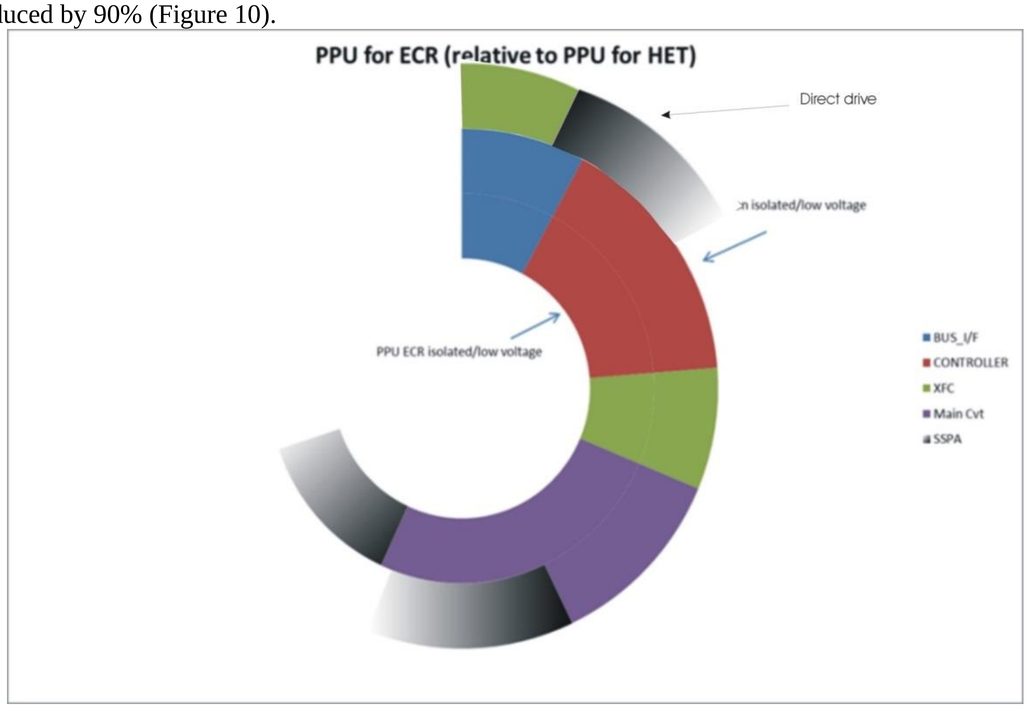


Figure 10. Cost reduction estimates of ECR PPU versus HET PPU.

V. Conclusion

The MINOTOR project is maturing the ECR thruster technology, and several significant achievements have been obtained, comforting the disruptiveness of the technology. In particular the performances have been measured in different facilities, the main physics of is understood and has been explained (although several areas still need to be studied) and a compact and reasonably efficient microwave generator technology has developed and demonstrated. Both the thruster and generator are at TRL4. The last part of the project will be mostly devoted to the lifetime assessment and improvement, and to the scale-up of the thruster.

Acknowledgments

This work was made in the framework of project MINOTOR that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730028.

References

1. J. Jarrige et al., *Characterization of a coaxial ECR plasma thuster*, Proceedings of the 44th AIAA Plasmadynamics.
2. J. Jarrige et al., *Performance Comparison of an ECR Plasma Thruster using Argon and Xenon as propellant Gas*, Proceedings of the 33th International Electric Propulsion Conference, vol. 420, 2013.
3. F. Cannat et al., *Experimental investigation of magnetic gradient influence in a coaxial ECR plasma thruster*, Proceedings of the Space Propulsion conference, Cologne, Germany, 2014.
4. F. Cannat et al., *Optimzation of a coaxial electron cyclotron resonance plasma thruster with an analytical model*, Physics of Plasmas, 22, 053503 (2015).
5. F. Cannat et al., *Experimental geometry investigation of a coaxial ECR plasma thruster*, IEPC-2015-90492
6. T. Lafleur, *Helicon plasma thruster discharge model*, Physics of Plasmas, vol. 21, no. 043507, 2014.
7. T. Lafleur et al., *Electron dynamics and ion acceleration in expanding-plasma thruster,* Plasma Sources Sci. Technol. 24 (2015) 065013
8. D. Packan et al., The "MINOTOR" H2020 project for ECR thruster development, IEPC-2017-547
9. J. Jarrige et al., Investigation on the ion velocity distribution in the magnetic nozzle of an ECR plasma thruster using LIF measurements, IEPC-2017-382
10. S. Correyero et al., , Measurement of anisotropic plasma properties along the magnetic nozzle expansion of an Electron Cyclotron Resonance Thruster, IEPC-2017-437
11. T. Vialis et al., Geometry optimization and effect of gas propellant in an electron cyclotron resonance plasma thruster, IEPC-2017-378
12. P.Q. Elias , Advances in the kinetic simulation of the microwave absorption in an ECR thruster, IEPC-2017-361
13. M. Merino et al., Wave Propagation and Absorption in ECR Plasma Thrusters, IEPC-2017-105
14. G. Sanchez-Arriaga et al., One-dimensional Direct Vlasov Simulations of Non-stationary Plasma Expansion in Magnetic Nozzle, IEPC-2017-106 (partial funding)
15. M.Wijnen et al. , Innovative Electric Propulsion trends, concurrent mission design and enabling technologies for a bold CubeSat Lunar Positioning, Young Visionary paper award, IEPC 2017 (partial funding)
16. S. Correyero et al., Ion acceleration in the magnetic nozzle of an ECR thruster: Comparison of experimental measurements with a quasi 1D kinetic mode, Conference SP2018-340
17. A. Sanchez-Villar et al., Advances in Wave-Plasma Modelling in ECR Thrusters, Conference SP2018-346
18. D. Packan et al., MINOTOR: Magnetic Nozzle Electron Cyclotron Resonance Thruster, Conference SP2018-490
19. S. Peterschmitt et al., Waveguide microwave coupling to amagnetic nozzle ECR thruster, Conference SP2018-496
20. T. Vialis et al., Separate measurement of magnetic and pressure thrust contributions in a magnetic nozzle ECR plasma thruster, Conference SP2018-499
21. E. Bourguignon et al., Power Processing Unit Activities atcThales Alenia Space in Belgium, Conference SP2018-122
22. C. Drobny et al., Development and testing of an in-situ thrust balance and characterization of a miniature Hall-effect thruster, Conference SP2018-94
23. Zhou et al., Collisional Effects in Non-stationary Plasma Expansions along Convergent-Divergent Magnetic Nozzles, Conference SP2018-332
24. S. Peterschmitt et al., Comparison of waveguide-coupled and coaxial-coupled ECR magnetic-nozzle thruster using a thrust balance, IEPC2019-188

25. D. Packan et al., H2020 MINOTOR: Magnetic Nozzle Electron Cyclotron Resonance Thruster, IEPC2019-875
26. S. Correyero et al., Effect of the initial electron distribution function in magnetic nozzle expansions, IEPC2019-818
27. A. Sanchez-Villar et al., , PIC/fluid/wave simulations of the plasma discharge in an ECR plasma thruster, IEPC2019-633
28. M. Merino et al., Fluid-kinetic propulsive magnetic nozzle model in the fully-magnetized limit, IEPC2019-254
29. J.-C. Porto-Hernandez et al., Electromagnetic-PIC simulation of an ECR plasma thruster, IEPC2019-232
30. Kinetic features and non-stationary electron trapping in paraxial magnetic nozzles 26 February 2018 G Sánchez-Arriaga, J Zhou, E Ahedo , M Martínez-Sánchez and J J Ramos Plasma Sources Sci. Technol. 27 (2018) 035002 (13pp)
31. S. Correyero et al., Characterization of diamagnetism inside an ECR thruster with a diamagnetic loop, Physics of Plasmas 26, 053511 (2019)
32. T. Vialis et al., Direct thrust measurement of an electron cyclotron resonance plasma thruster, Journal of Propulsion and Power, Volume 34, Number 5, September 2018