The "MINOTOR" H2020 project for ECR thruster development

IEPC-2017-547

D. Packan[1], P.Q. Elias, J. Jarrige
ONERA, Palaiseau 91120, France

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

G. Peyresoubes[3]
THALES MICROELECTRONICS (TMI), Etrelles 35370, France

K. Holste[4], P. Klar
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]
SAFRAN AIRCRAFT ENGINE (SAFRAN), Paris 75015, France

and

M. Mares[7], A. Hoque, P. Favier
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 [15], 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 first results obtained with ECRA have been encouraging [1-7], but 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 TRL4/5.

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.

		Research institute	University	Industry	
1	ONERA	France	X			experimental investigations, coordinator
2	UC3M	Spain		X		numerical modeling
3	TMI	France			X	high efficiency microwave generator
4	JLU	Germany		X		high power tests
5	TAS-B	Belgium			X	PPU impact and roadmap
6	SAFRAN	France			X	system impact and roadmap
7	LUP	France			X	managing partner

Table 1. Composition of the MINOTOR consortium.

II. Objectives of MINOTOR

The main objective of the project is to reach TRL4/5 for the ECRA technology of electric propulsion, in order to demonstrate the potential of this technology in comparison to other technologies in a large range of thrust levels. To reach this goal, it is planned to have achieved the following objectives by the end of the project:

- 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).
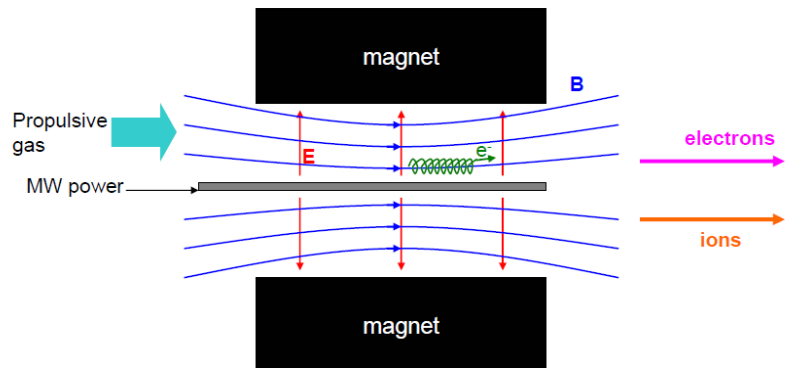
B.   Physics of the thruster

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 $\omega = \dfrac{e.B}{m_e}$. 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.
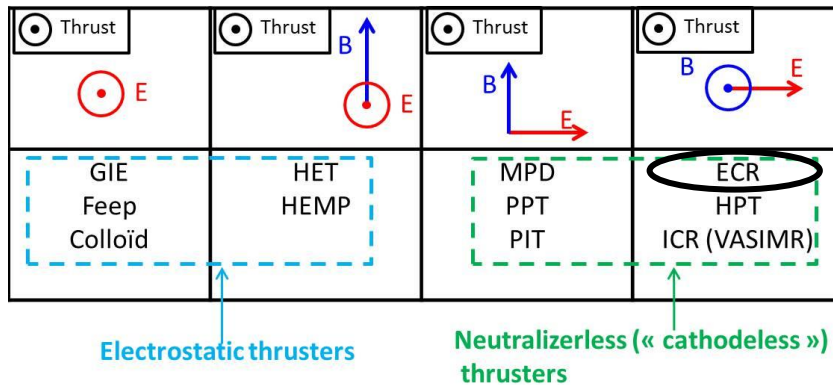

Table2: Categorizing of thrusters depending on the acceleration principle. ECRA is an ECR thruster (circled)

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	Lower recurring cost Higher reliability
	Single fluidic line	Lower recurring cost
	Low Xe purity acceptable	Lower recurring cost (ground testing) Lower cost of flight propellant Lower cost Xe tank
	Reacting gases acceptable (e.g. O_2)	Compatible with "air breathing" Compatibility with all alternative propellants.
No fragile or complex parts (no grids, etc...), low part number	Simple design	Lower recurring cost Higher reliability Longer lifetime
Magnetic nozzle	Thrust vectoring	Lower recurring cost (no gimbal mount needed)
	Ambipolar acceleration	No Child law limit to thrust per unit area (similar to HET)
	Magnetic shielding	Longer lifetime Higher efficiency
Microwave power = only electrical input	Simplified PPU	Lower recurring cost
	DC uncoupling of thruster and PPU	Lower recurring cost (no galvanic isolation of PPU)

Table3: Main advantages of the ECRA thruster compared to current mature technologies. Lower cost, higher reliability and longer lifetime have been highlighted in green, blue and pink, respectively

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)
	Separated	GIE	ICR-VASIMR	
IONIZATION AND ACCELERATION ZONES	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.
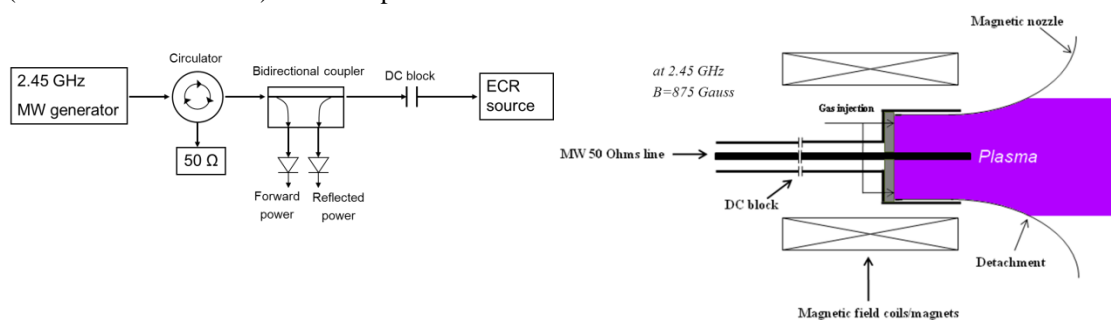

Figure 2: Typical microwave circuit used (left) and thruster configuration (right)

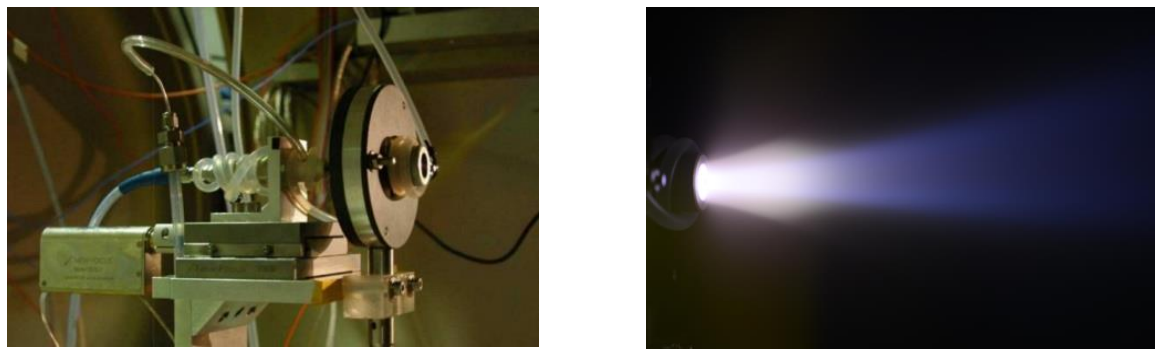Preliminary designs were developed (Figure 3).

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 not far from mature technologies at that thrust level, although

comparison is difficult as few mature technologies have been developed and fully characterized at that power level, ECRA included (lifetime is still to be studied). 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.

Different studies are being conducted on magnetic nozzle thrusters around the world, in the US ([8], [9], [10], [11]), in Japan [12], in Europe ([16], [17], [18], [19]) and in Australia, most of them on HPT. Indeed ONERA is one of the only laboratory working on an ECR thruster with magnetic nozzle, to the knowledge of the authors, although several investigations on ECR thrusters were conducted in the past ([13], [14]).

The potential of ECRA can be seen in Figure 4, compared to selected magnetic nozzle thruster experiments. Few efficiency data for magnetic nozzle thrusters have been obtained in the literature (they are all helicon thrusters), most have been taken at high power and some are plotted in the figure. The trend for HET is also placed in the figure, showing the increasing performance with size/power as already mentioned. Such a trend is also expected for ECRA (dotted red line). Thus, one of the goals of the project will be to test the upscaling of the thruster, and a significant increase in efficiency is expected.
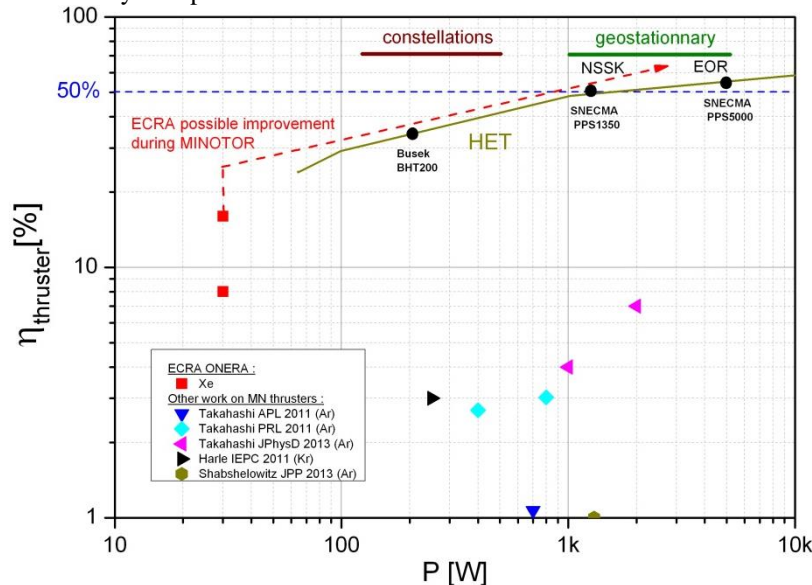

Figure 4. Efficiency of ECRA and other cathodeless thruster, HET thruster performance, and extrapolation possible for ECRA performance

Although preliminary experiments have been conducted and encouraging results have been obtained, currently the ECRA thruster has several interrogations due to its low TRL status:

- It lacks a predictive model to use in order to help optimise its design and determine its envelope of performance and scale-up capabilities;
- Only a very small portion of the ranges of its parameters have been studied. Several important ones (thruster geometry, wave coupling strategies, effect of wave frequency, magnetic field topology inside and outside the thruster) must be addressed in depth. Thus, the thruster is far from being optimised;
- It has been tested at low power only (~30W), but a demonstration at higher power would be needed to investigate its potential for the large satellite market;
- Some of its supposed features have not been fully demonstrated, such as magnetic thrust vectoring and long lifetime;
- No off-the-shelf efficient MW PPU has been identified at this time, therefore the technology has to be demonstrated not to be a show-stopper;
- The impact of ECRA at system level has not been examined in detail.

IV. Organization of the consortium

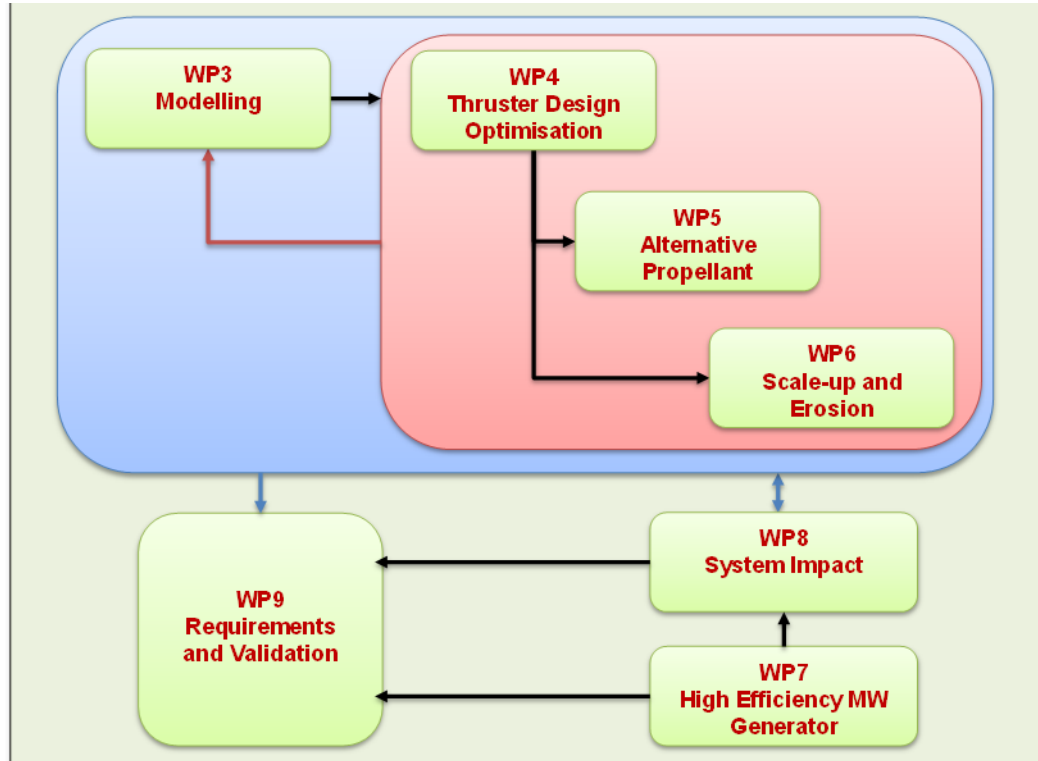The organization of the technical work-packages of the MINOTOR project is shown in Figure 5.

Figure 5. 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 <u>efficiency</u> 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 proposal is organized around three main tasks: thruster development (the main activity), MW PPU demonstration, and systems impact and roadmaps. The work packages are as follows:

- **Thruster development:**
    - o Physics understanding and model development (WP3: Modelling);
    - o Parametric study and optimisation of the design (WP4: Thruster Optimisation);
    - o Specific topics of importance (WP5: Alternative propellants and WP6: Scale-up and lifetime).
- **MW PPU technology demonstration:**
    - o WP7: High efficiency microwave generator.
- **Systems impact and roadmaps:**
    - o WP8: System impact (PPU, thruster, platform);
    - o WP9: Requirements and Validation.

The roles of the different partners are as follows:

- ONERA is the project coordinator, and is in charge of most experimental investigations of the thruster configuration, and of PIC code development.
- UC3M will develop the main hybrid code and implement the numerical modelling of the thruster.
- TMI will demonstrate a high efficiency microwave generator technology.
- JLU will conduct the higher power tests (1 kW) and the erosion test on the 200 W prototype.
- TAS-B will investigate the impact of the ECRA technology on the PPU architecture and cost.
- SAFRAN will provide expertise in electric propulsion thruster production and performance.
- LUP will help on the project management.

The main technical work packages are briefly described below.

A. WP3: modelling

Different models and codes will be developed in the course of the project. Once they become mature they will be used for guiding the experiments and perform parametric studies to optimize the performances of ECRA. Two main codes will be developed: SURFET and ROSEPIC.

1. SURFET

The main code to be used in the course of the project is the SURFET code from UC3M. SURFET will consist of 4 separate modules, each with well-defined goals and tailored to one part or process of the ECRA. They will be merged at this end of development to obtain the global SURFET code. SURFET will build on the experience of UC3M on hybrid codes for electric propulsion systems (HALLMA, EP2PLUS codes), wave codes (HELFLU) and magnetic nozzle codes (DIMAGNO). The four modules of SURFET are described in Table 2.

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

A separate paper discusses the wave-plasma numerical modeling, which is one of the problems that the codes to be developed in MINOTOR must tackle: "Wave Propagation and Absorption in ECR Plasma Thrusters" [20], IEPC-2017-104, M. Merino et al.

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.

A separate paper ([22]) describes the advances of the PIC code: P.Q. Elias, *Advances in the kinetic simulation of the microwave absorption in an ECR thruster*, IEPC-2017-361

B. WP4: Thruster optimization

This work package is composed of experimental investigations of different thruster design, configurations and parameters, guided by the numerical modelling of WP3, and on the same set of parameters described above.

The goal is to:
• Determine experimentally the best parameters;
• Validate the models;
• Help design an optimized thruster.
This work package will be performed at the 50W power level with Xenon.

The parameters to be investigated are:

- Thruster geometry;
- Wave coupling strategy / effect of frequency;
- Magnetic field topology / magnetic nozzle;
- Thrust vectoring.

The diagnostics will include: thrust measurement, beam profiles (current, energy), and LIF for accurate ion velocity profiles.
Three separate papers ([21], [23], [24]) describe the advances in this work package:
- J. Jarrige, S. Correyero-Plaza, P.Q. Elias, D. Packan, *Investigation on the ion velocity distribution in the magnetic nozzle of an ECR plasma thruster using LIF measurements*, IEPC-2017-382
- S. Correyero-Plaza, J. Jarrige, D. Packan, E.Ahedo, *Measurement of anisotropic plasma properties along the magnetic nozzle expansion of an Electron Cyclotron Resonance Thruster*, IEPC-2017-437
- T. Vialis, J. Jarrige, D. Packan, *Geometry optimization and effect of gas propellant in an electron cyclotron resonance plasma thruster*, IEPC-2017-378

C. WP5: Alternative propellants

The ECRA technology is particularly well suited to the study of alternative propellants, because it has no element that is chemically sensitive (such as a neutralizer or fragile/small metal elements). Thus, a wide variety of propellant will be studied in the course of the project.
As a baseline, numerical and experimental investigations are planned in the MINOTOR project for the following propellants: Kr, Ar, Ne, Xe, CO_2, N_2, O_2, air. Numerical simulations only are planned for selected others. If significant advantages are determined for some of these, experiments could be planned.
The numerical simulations will study the effect of the propellants. The thruster design will be optimized numerically for only two propellants, Kr being one of them, and the two designs will be tested experimentally. Other propellants will be numerically and experimentally tested on unoptimized designs.

D.   WP6: 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. Besides, these powers are representative of specific applications: 200W for constellations, 1kW for NSSK of geostationary satellites. Furthermore, it is recognized that a test at 1 kW is representative for the behaviour of the thruster at higher thrust levels.

The actual optimized thruster scale-ups will be studied in the second half of the project, in order to profit from the numerical codes developed in WP3. Experiments will then be conducted at the large JUMBO vacuum facility at JLU in Giessen. JLU will develop a specific thrust balance having the proper sensibility for the 200W test.

Erosion tests are necessary because erosion phenomena that limit the life of electric thrusters are difficult to model. A 1000 hours test is planned on a model ECRA thruster.

E.   WP7: High efficiency microwave generator

The goal of this work package is to demonstrate than a high efficiency (>85%) 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.

The bandwidth has not been specified because it has experimentally not been identified as an important parameter for ECRA. The study will develop an innovative technology based on new elementary amplifier (developed by TMI) and a new, patented power combiner (recent TMI patent).

The study will consist of three steps:
- Development and implementation of an elementary high efficiency amplifier at 25 W;
- Development of an efficient power combiner;
- Development and prototyping of complete package of the combined amplifiers (x4) and power combiner, to reach 100W, and demonstration on the ECRA thruster in vacuum.

F.   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.

This work package is organized accordingly, and the goal will be to confirm these impacts and identify others, and to characterize their effect quantitatively in terms of relative cost reduction. A final assessment of the impacts will be done at the end of the project following the evolution of the thruster design.

G.   WP9: Requirement and Validation

The goal here is threefold:
- Provide a set of reference EP data to compare to ECRA performance in the course of the project;
- Follow the ECRA and microwave generator performance evolutions during the course of the project;
- Provide the final analysis and concatenated roadmaps for future activities.

In particular, in light of the performances of ECRA, either demonstrated or calculated in different thrust ranges during the project, applicability to different applications (LEO, MEO, GEO, transportation, exploration) will be explored and a GO/NOGO analysis will be applied to the ECRA technology.

V. Conclusion

The MINOTOR project will help mature the ECR thruster technology, develop reliable performance measurement tools for magnetic nozzle thruster and high-end simulation codes for electric propulsion, and improve the efficiency and design of ECRA, to the point where the performance and applicability ranges of the thruster can be fully assessed. If the developments lead to an efficient and reliable thruster, its simplicity and cost advantages could be a disruptive force for electric propulsion for all the concerned platforms.

Acknowledgments

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. L. Williams, M. Walker, "*Plasma structure and ion acceleration of a helicon plasma source*", IEEE Trans. Plasma Sci., vol. 43, No. 5, p. 1694 (2015)
9. O.V. Batishchev, "*Minihelicon Plasma Thruster*", IEEE Trans. Plasma Sci., vol. 37, No. 8, p. 1563 (2009)
10. A. Shabshelowitz, A. D. Gallimore, "*Performance and probe measurements of a radio-frequency plasma thruster*", J. Propul. Power, vol. 29, No.48, p. 919 (2013)
11. Ferrario, J. M. Little, E. Choueiri, "*Propulsive performance of a finite-temperature plasma flow in a magnetic nozzle with applied azimuthal current*", Phys. Plasmas, vol. 21, 113507 (2014)
12. "*Effect of magnetic and physical nozzles on plasma thruster performance*", K. Takahashi et al., Plasma Sources Science and Technology, Volume 23, Number 4
13. "*Physics of Electric Propulsion*", R. Jahn, 1968.
14. "*An experimental and theoretical study of the ECR plasma engine*", J.C. Sercel, thesis, Caltech 1993
15. M. Merino, E. Ahedo, *Contactless steering of a plasma jet with a 3D magnetic nozzle*, Plasma Sources Science and Technology, Vol 26, N°9, p 095001, 2017
16. M. Merino & E. Ahedo, *Plasma detachment in a propulsive magnetic nozzle via ion demagnetization*, Plasma Sources Science and Technology 23, 032001 (2014)
17. M. Merino & E. Ahedo, *Effect of the plasma-induced magnetic field on a magnetic nozzle*, Plasma Sources Science and Technology 25, 045012 (2016)
18. M. Merino & E. Ahedo, *Contactless steering of a plasma jet with a 3D magnetic nozzle*, Plasma Sources Science and Technology 26, 095001 (2017)
19. J. Navarro Cavallé et al., *Experimental Performances of a 1-kW HPT by means of Plasma Diagnosis*, IEPC-2017-447
20. M. Merino et al, *Wave Propagation and Absorption in ECR Plasma Thrusters*, IEPC-2017-104
21. J. Jarrige, S. Correyero-Plaza, P.Q. Elias, D. Packan, *Investigation on the ion velocity distribution in the magnetic nozzle of an ECR plasma thruster using LIF measurements*, IEPC-2017-382
22. P.Q. Elias, *Advances in the kinetic simulation of the microwave absorption in an ECR thruster*, IEPC-2017-361
23. S. Correyero-Plaza, J. Jarrige, D. Packan, E.Ahedo, *Measurement of anisotropic plasma properties along the magnetic nozzle expansion of an Electron Cyclotron Resonance Thruster,* IEPC-2017-437
24. T. Vialis, J. Jarrige, D. Packan, *Geometry optimization and effect of gas propellant in an electron cyclotron resonance plasma thruster,* IEPC-2017-378