iFACT-MP: MULTI-KILOWATT IODINE ELECTRIC PROPULSION DEVELOPMENT

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ABSTRACT:

iFACT-MP (iodine Fed Advanced Cusp field Thruster for Mid-Power) aims to develop Europe's first iodine fed propulsion subsystem for the 3-5 kW range. This encompasses the upscaling of the Advanced Cusp Field Thruster (ACFT) and the development of the full iodine fluidic chain. To validate the necessary control and operational schemes, a breadboard PPU will be developed that includes supplies, telemetry and functionalities to enable autonomous control of the thruster subsystem. A key building block towards enabling a completely iodine-based EP chain is an iodine fed neutraliser. For this purpose, further improvements and modifications on C12A7 emitter ceramics will be performed. Accurate characterisation of the developed thruster subsystem's performance will be enabled by an optical iodine flow meter. A suitable iodine compatible vacuum chamber including a thrust balance and diagnostics for this power range will be developed to perform a full characterisation and 500 hr endurance testing of the subsystem.

1. INTRODUCTION

The satellite market is seeing a growing demand for propulsion solutions that satisfy the need for high efficiency in terms of specific impulse, therefore enabling a lower propellant- and higher payload-share in relation to the whole satellite, or more satellites to be launched at once. With the requirements for higher thrust levels in order to comply with larger satellites and increased availability, electric propulsion (EP) solutions in the kilowatt power range are required. Whereas such subsystems are available that use conventional noble gas propellants, their high cost – with xenon prices recently exceeding 20,000 €/kg at their peak – leads to an excessive share of the propellant cost to the whole satellite. Further, Europe's strong dependence on international noble gas production has been unveiled.

As alternative to the established noble gas xenon, a propellant is desired that is competitive in terms of performance, is sustainable, at the same time affordable and available from European sources in order to ensure non-dependence from other countries. Iodine excels in these points and offers even more advantages which are also summarised in Table 1. First of all, iodine offers similar performance to xenon, which is the state-of-the-art propellant in terms of performance. For EP propellants, the most important properties are a high atomic mass in order to maximise the thrust per ionisation and acceleration event with the available power from the satellite. Further, for a high efficiency a low ionisation potential and a large collision cross-section is desired, where iodine even exceeds xenon's properties. Krypton on the other hand, the other major noble gas propellant which is attractive due to its lower cost, exhibits the disadvantage of significantly lower molecular mass and being comparably hard to ionise. In comparison to the noble gases, a major advantage of iodine besides its extremely low cost is its exceptionally high storage density, as it is stored in its solid form at a conservative density of 3.9 kg/L (due to the shrinkage during casting, the maximum density is 4.9 kg/L). With iodine's vapour pressure being limited to 128 mbar, further no high-pressure vessels or regulators are required and enabling the tank shape to be adapted to the available space. The solid propellant results in operational advantages as well, since the iodine EP subsystem can be integrated into the satellite while it is already loaded, omitting the cost and time-consuming propellant loading procedure on the launch site.

Traditional noble gas propellants are extracted from the atmosphere, where they are present as traces at only 1.1 ppm for krypton and 0.087 ppm for xenon. This results in an extremely energy consuming process to obtain the high purities required in EP. The whole chain to obtain the Primary Krypton Concentrate, which is then further purified typically using the Khrom-3 process, results in an energy consumption in the range of 28.4 MWh [1] for a single kilogram of xenon, being in the order of the electrical energy consumed by nine German households [2] per year. Iodine on the other hand, in case of recycling from thiosulfate solution containing 6 % of iodine, requires only around 1 kWh, dividing the total power consumption of the iodine recycling plant by its production rate. For krypton the energy consumption is not as high as for xenon due to the larger yield, however still being > 3000 x higher than for recycled iodine. Germany alone has sufficient iodine recycling capacity to cover the estimated spacecraft market, ensuring non-dependency. The major drawback of iodine to be considered for missions is its low TRL of only 2-3 for the desired 3-5 kW at this time. To overcome this last barrier, activities such as iFACT-MP are required.

	Xenon 	**Krypton** 	**Iodine** 
Atomic mass in g/mol	131.3	83.8	126.9
First ionisation potential in eV	12.1	14	10.5
Peak collision cross-section in 1e-16 m^2	4.8	4.2	6.0
Storage density at 30°C in kg/L	1.87 (at 150 bar)	1.2 (at 300 bar)	3.9 (at ambient pressure)
Cost in €/kg	>15000	>2000	60
Energy consumption in kWh/kg	28410	3556	~1
Maturity at 3-5 kW	TRL 9	TRL 6	TRL 2/3 *

* higher TRL demonstrated in lower power classes, raising the confidence the TRL goals are achievable

At the Laboratory for Enabling Technologies at Airbus Friedrichshafen the Advanced Cusp Field Thruster (ACFT) has been developed and extensively tested with iodine as propellant. The thruster technology offers major advantages regardless of the propellant used: Firstly, the gridless design eliminates major challenges GIEs are facing such as grid erosion, beam events as well as the high cost of their manufacturing. Further, the well contained plasma discharge leads to effectively no discharge chamber erosion, which is a major lifetime limiting mechanism for HETs. The compact and simple mechanical design without complex parts enables low unit costs and high degrees of industrialisation and is extremely robust against the loads seen during launch. In terms of thruster operation the ACFT offers an unparalleled flexibility regarding the flow rate and anode voltage, allowing the operational point to be tailored towards the application and trading specific impulse (Isp) with Power-To-Thrust-Ratio (PTTR). The undemanding nature regarding the anode voltage allows unregulated anode supplies to be used, enabling high cost savings for the notoriously expensive PPU development. Therefore, the combination of the ACFT with iodine as green propellant is an ideal solution for a low-cost, high-performance and universally applicable electric propulsion subsystem. The thruster and feeding principle is patented by Airbus [3,4], so that this technology is not governed by any ITAR or EAR regulations.

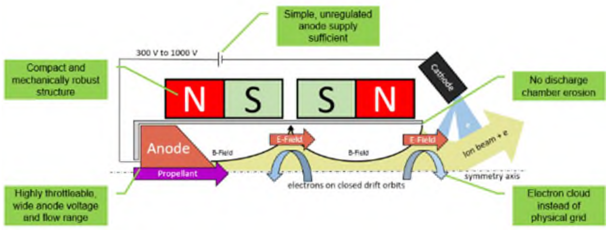

Figure 1: Schematic of the ACFT illustrating major advantages of the technology.

Within the recent Horizon2020 project iFACT (iodine Fed Advanced Cusp field Thruster) the ACFT was successfully developed for the 300 W level and endurance tested for over 3000 h on iodine [5]. Further, a 10 W cubesat version and a 1 kW thruster with a novel scaling scheme were developed and characterised, demonstrating the exceptional scalability of the thruster concept. The electron emitting material ($12CaO \cdot 7Al_2O_3$ named as C12A7) was improved to higher current density for ionisation of the iodine in the cathode. One of the potential show-stoppers for iodine on platform level, the compatibility with typical spacecraft materials, has been verified experimentally in iodine vapour exposition and sputtering studies as is detailed in [7].

2. TECHNICAL WORK PLAN

As a part of iFACT-MP, the ACFT developed and tested in iFACT for 300 W anode power shall be upscaled to challenge current state-of-the-art xenon thrusters, while operating with iodine. Figure 2 illustrates the comparison of high TRL European state-of-the-art xenon thruster performance in the 3 kW to 5 kW region and the 300 W iFACT thruster technology. Further, the estimated improvement as a result of the upscaling of the 300 W iFACT thruster to the 3 kW to 5 kW range is indicated. Similar to HET scaling, the PTTR is in the same order of magnitude, while the specific impulse improves significantly.

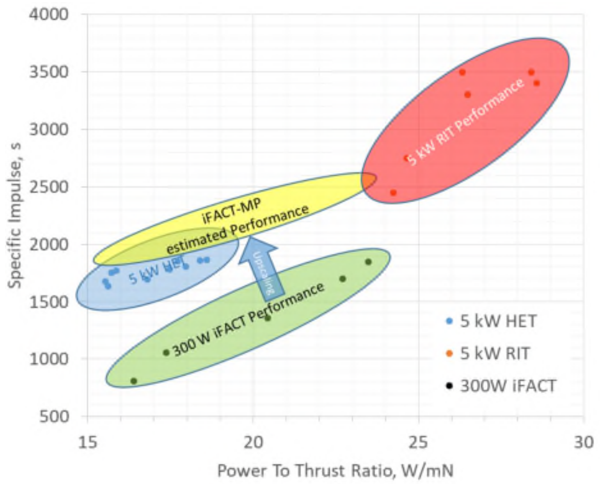

Figure 2: Performance map comparing state-of-the-art technologies to the 3-5 kW ACFT under development.

With the iFACT project, Europe has taken the leadership in iodine EP in the sub kW power range. To manifest and further expand that position in the higher power classes (>3 kW), a development program is required to raise the maturity level to a point where a qualification program can be initiated. The here proposed follow-on project iFACT-MP is aiming to achieve that by developing all the essential building blocks required for a mid-power iodine EP system, which includes:

- **Specification**: Analysis of the market and platform needs to derive requirements for an attractive EP subsystem
- **Thruster**: Upscaling of the ACFT to the 3-5 kW power range
- **Cathode**: Development of an iodine-fed hollow cathode using C12A7 emitters with enhanced performance
- **Fluidics**: Full chain with heated tank, flow control and piping
- **Test Facility**: iodine compatible vacuum chamber that enables characterisation and endurance testing at the required power level
- **Diagnostics**: Development of an optical sensor to measure the iodine flow rate in-situ

To be able to achieve this, a powerful consortium has been assembled uniting the major European players in iodine EP:

- **Airbus**
  - o **Friedrichshafen** team as pioneer in iodine EP
  - o **Toulouse** team as system, EP and fluidics experts
  - o **Elancourt** team as PPU specialists
- **Aerospazio** as major European EP test provider with iodine experience
- **Fraunhofer IKTS** as leading research institution for performance-enhanced C12A7 emitters for an iodine-fed cathode
- **University of Pisa** as experts on spectrophotometric iodine flow measurement
- **EASN** as leading aerospace networking, dissemination and communication entity to maximise the impact of the activity

The project targets the performance objectives listed in Table 1 for the components of the subsystem and test environment, consisting of the thruster, cathode, fluidics and PPU breadboard as well as the vacuum test facility and iodine flow sensor.

Table 1: KPIs for the iFACT-MP project.

Key Performance Indicator	State-of-the-Art 3-5 kW EPS (Xe HET)	iFACT-MP EPS
Subsystem Cost	100 %	80 %
Subsystem Volume	100 %	35 %
Subsystem Mass (thruster, cathode, flow control)	12 kg	< 10 kg
Propellant Cost	5000 - 15000 €/kg	< 100 €/kg
Integration Cost	100 %	80 %
Specific Impulse	1630 - 1860 s	> 1800 s
PTTR	15.5 - 18.4 W/mN	16 - 24 W/mN
Propellant carbon footprint	685 t_{CO2e}/MNs	< 1 t_{CO2e}/MNs

Figure 3 illustrates the major building blocks of the thruster development that are addressed in iFACT-MP. For the subsystem, the central element is the ACFT thruster that will be up-scaled building upon the previously developed 300 W iFACT thruster. To feed the thruster, a fluidic chain needs to be developed able to supply the iodine vapour flow rates required in that power range. This will consist of a heated tank, flow controller and piping for both the thruster and the cathode, a typical iodine fluidic chain is illustrated in Figure 4: Schematic and principle of a typical iodine fluidic chain. The vapour pressure is controlled through control of the tank temperature, whereas the flow rate is regulated by a valve. To avoid iodine condensation, the whole fluidic chain including the thruster is heated.

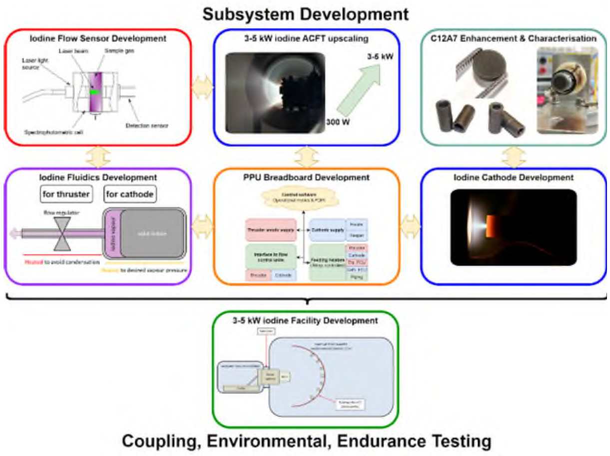

Figure 3: Building blocks addressed in the iFACT-MP project.

To enable in-situ characterisation of the flow rate, an optical sensor will be developed and integrated allowing rapid characterisation of the thruster performance at different operational points. The most challenging element in iodine EP is an iodine fed cathode. Building on the achievements within the ESA Expro+ project IcoN, a cathode using a C12A7 emitter will be developed, the only currently known iodine compatible emitter material. To achieve the required current range, the C12A7 will be further enhanced through structuring and increasing the melting point. Due to the high challenges associated with iodine fed cathode development, a noble gas fed cathode will be investigated as backup solution to ensure successful development of a working thruster subsystem.

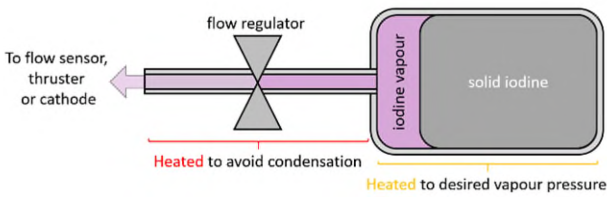

Figure 4: Schematic and principle of a typical iodine fluidic chain.

To control all elements of the subsystem autonomously, a PPU breadboard will be developed including all the required functionalities. As there is currently no facility available to test an iodine thruster at that power level within Europe, such a facility including the necessary diagnostics will be developed and used for the coupling and endurance testing to experimentally verify the developed subsystem's performance.

3. Project Planning

Figure 5 presents the project schedule for the activity. At the time this proceeding is written, the requirements engineering was close to finalisation. Based on an analysis of the current and projected satellite market, requirements have been derived for a competitive EP subsystem that challenges state-of-the-art solutions. Based on that, equipment specifications for the thruster, fluidics, breadboard PPU and the mass flow meter are derived. This step will be concluded by the SRR, which is the starting point for the subsequent design phase. The basic design decisions will be reviewed in a PDR, whereas the final, refined design will be reviewed in a CDR. This design freeze kicks off the preparation of the manufacturing phase, which will be finally initiated after successful conclusion of the MRR. As soon as the parts and units become available, each building block will be tested and characterised. The TRR then kicks off the final phase where the subsystem's performance is experimentally demonstrated in an initial coupling test, mechanical environmental testing on one thruster unit and finally a 500 h endurance test on a second thruster unit with complete subsystem, consisting of fluidics and power electronics.

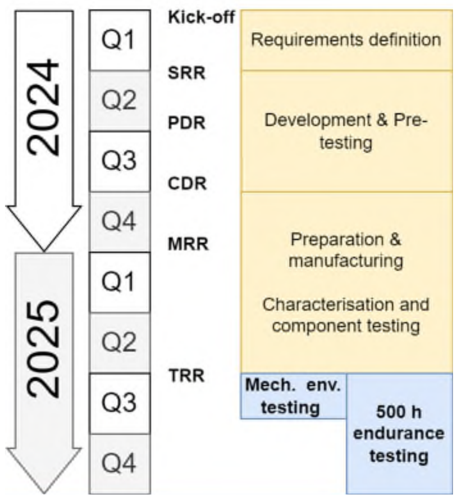

Figure 5: Project schedule for iFACT-MP.

4. ACKNOWLEDGEMENTS

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