Reformulating the Concept of Ionic Liquid fueled Ion Thrusters

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Ionic-Liquid Thrusters (ILT) have been introduced, designed and developed for In-space propulsion devices and specifically for small spacecrafts. Currently developed ILT [Paulo C. Lozano et al. MRS BULLETIN, vol. 40, Oct 2015, pp. 842-849] propulsion systems are consisting of needle emitter arrays spaced by a few hundreds of microns and infused with an Ionic Liquid. When exposed to an electrostatic field in the range of 1 Volt / nanometer at tip apex, positive or negative molecular ions that compose the liquid can be evaporated selectively and directly from the tip surface, then swiftly accelerated to highest possible velocities thus producing thrust. The beauty of this approach is that because the ions come out directly from the liquid surface, the device can be drastically miniaturized.

In-space propulsion devices for small spacecraft are rapidly increasing in number and variety. Although a mix of small spacecraft propulsion devices have established flight heritage, the market for new propulsion products continues to prove dynamic and evolving [NASA/TP 2021 0021263, State-of-the-Art Small Spacecraft Technology]. Indeed guiding and controlling very small satellite trajectories as well as their orbital drift still necessitate to develop, produce and commission compact, efficient, and robust propulsive systems.

Since 2017 we have been building a working group with the aim at reversing our approach originally centered onto nanofabrication and going –this time “From the nanosciences back to space”. Our motivations were indeed to bring back to the space propulsion field the ideas, concepts and devices we have been capable to develop as they relate to Ionic Liquid Ion Sources (ILIS) physics and technology [J. Gierak, P. Lozano et al. Invited lecture EIPBN conference 2017, 6A-3]. In this work we will detail our innovations and development route that have allowed our team to reformulate the concept of Ionic Liquid fueled thrusters allowing higher performances, both in firing lifetime, fuel degradation kinetic and measured thrust.

Reformulating the Concept of Ionic Liquid fueled Ion Thrusters

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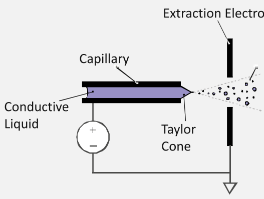
Abstract:

In this work we present our work aiming at bringing back to the space propulsion field the ideas, concepts and technologies we have been capable to develop, engineer and set as market references for nanofabrication tools using Focused Ion Beams (FIB).
The technologies we develop relate to Electro-HydroDynamic Ion Sources primarily using Liquid Metals (LMIS) and more recently using ionic Liquids (ILIS)
In this work we detail our innovations and development route that have allowed our team to reformulate the concept of Ionic Liquid fueled thrusters allowing higher performances, both in firing lifetime, plume stability, fuel degradation kinetic and measured thrust.

1. Ionic Liquid Ion Source - Operation principles & Promises



Balance (Taylor 1964)

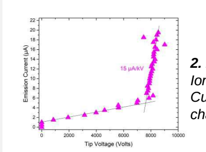
$$\frac{1}{2}\varepsilon_0 E^2 = \gamma\left(\frac{1}{R_1}+\frac{1}{R_2}\right)$$

- Extreme electric field stress (~ 10⁹ V/m),
- Surface tension,
- Internal pressure caused by liquid flow

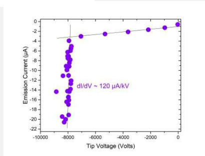
$$\Delta p = p_{int} - p_{ext} = \gamma(1/R_1 - 1/R_2) - (1/2)\varepsilon_0 E^2$$

- Ionic Liquid = Finite conductivity
- Time for the charges to relax @ surface

$$\frac{1}{2}\varepsilon_0 E^{*2} - \frac{1}{2}\varepsilon_0 E_{int}^2 \approx 2\frac{\gamma}{r^*}$$



***2. Positive** Ion emission – Current / Voltage characteristic*



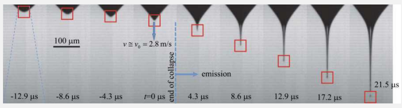
***3. Negative** Ion emission*

***1. Electro HydroDynamic (EHD) ion emitter** - 1959 C.D. Hendricks "Electrical atomization or spraying of liquids in vacua Source of charged heavy particles for electric propulsion systems"*

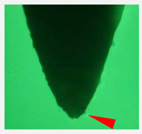
2. Ionic Liquid Ion Source - Limitations

Existing known limitations of Ionic Liquid Ion Sources (ILIS) & Thruster (ILT)

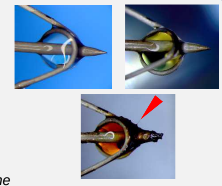
- *Ionic Liquid Ion Sources are NOT classical "jet on a cone" = Emission site highly mobile*
- *Limited emission stability and thrust sustainability due to lack of control on Taylor cone creation, stabilization and dynamics,*
- *Electrochemical window of the Ionic Liquid + high emission fluxes = Rapid fuel degradation over time*
- *Reported thrust values in the literature way lower than theoretical expectations*
- *Limited control of Pure Ionic Regime due to hydrodynamic instabilities Ion-Droplet mixed emission regime*
- *Unstable droplets, (Rayleigh criteria) fragmentation in the acceleration region*



***4. Shape of an emitting Ionic Liquid "Jet on a cone"** Gañán-Calvo, A. M. et al. Sci. Rep. 6, 32357 (2016)*

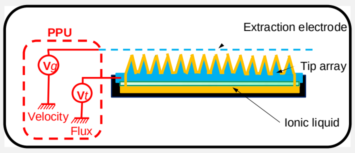


***5. 1MeV TEM image** of the apex of an emitting ILIS fueled with EmiBF4 (CNRS-CEA)*

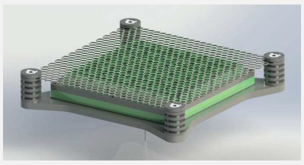


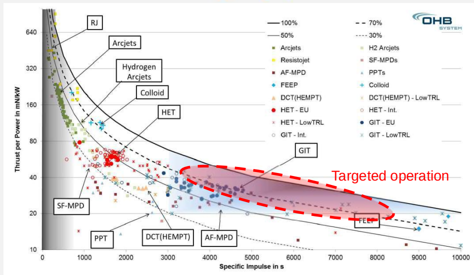
***6. EmiBF4 fuel ageing** @T_0, T_0+10mins, T_0+60mins*

3. Our reformulated Ionic Liquid fueled Thruster Concept & Performance Target(s)



***7. Schematic and CAD design of the final Ionic Liquid Thruster** developed and tested in this work with 49 unit cells capable of delivering each up to 100µA / 8kV extraction voltage*





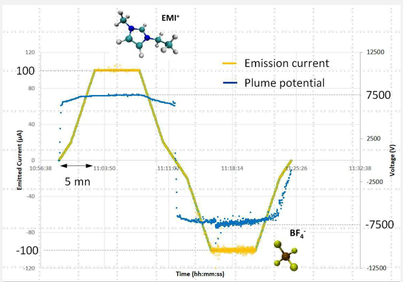
Thruster Main Characteristics

- *"Arrayable" / Scalable Propulsion architecture* — *Cell (unit = 1cm²) – Matrix 3x3 up to 7x7*
- *Conventional Ionic Liquid fuel* — *1-Ethyl-3-methylimidazolium tetrafluoroborate (non toxic, easily available, low cost,…)*
- *High Ion extraction voltages (6 to 8kV)* — *= Fast ions and Improved Plume collimation (Immersion lens effect)*
- *High emission Flux stability versus Time* — *= Better plume directivity and thrust vector keeping*
- *Externally wetted NanoWires tips (Patented)* — *< 5% (nano-Amperes to 100 micro-Amperes / cm²)*

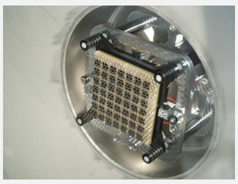
= Plurality of potential emission sites operating in the Pure Ionic Regime (PIR)
= Distributed emission® limits ion depletion and counter ion accumulation (Insoluble tar formation)
= Electro-chemical window

***8. Thrust per Power f(Isp)** From Peukert, M. and Wollenhaupt, B. "OHB-System's View on Electric Propulsion Needs", EPIC Workshop, 2014*

4. Measured performances



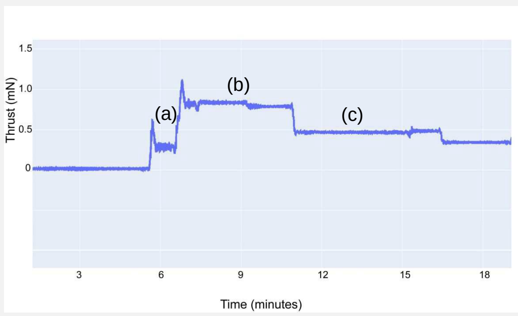
***9. Constant polarity firing (100µA/cm²)** can be maintained for duration from 5 to 30 minutes revealing intrinsic emission stability.*



***10. Ionic Liquid Thruster with 49 emission cells** installed in the test chamber developed by and at ION-X*

***11. Thrust measurement** of the 49 emission cells ILT*
- *Positive emission constant polarity*
- *8kV ion potential*
- *Emitted currents*

(a) 1 mA duration ~ 1 minute
(b) 3 mA duration ~ 4 minutes
(c) 2 mA duration ~ 5 minutes



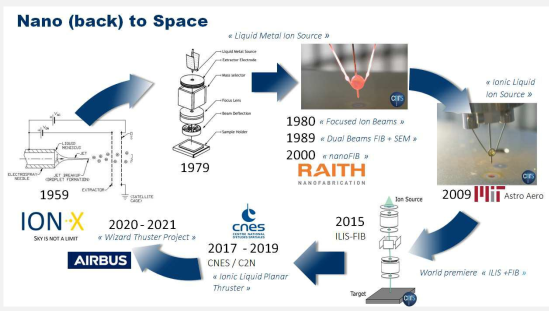
5. Conclusions & perspectives

Owing to our gathered expertise we have been capable of reformulating the approach of the Ionic Liquid fueled Ion Thrusters while using the well-known Ionic Liquid EmiBF4.
***Innovations:** (i) Emitters structure & materials, **(ii)** Independent operation control (Flux / Particle velocities) **(iii)** Fuel management and **(iv)** Ion emission polarity plume and vessel neutralization at the cell unit level,*
***Sci. & Technol. Approach:** micro- and nano-electronics derived materials and processing methods, based on the C2N-CNRS leading expertise (know-how and equipment) = Highest performance EHD metal ions sources known to date*

In this work we have demonstrated:

- *Stable and reproducible emission characteristics from a matrix of emitting tips maintaining unipolar propulsion sequences up to several tens of minutes with no detectable degradation of the Ionic Liquid (EmiBF4) fuel (RMN analysis),*
- *Better control of emitted droplets and of the terminating Taylor Cone(s) jet(s) fragmentation detrimental effects,*
- *Unprecedented lifespan of both the emitter, the extraction electrode and the circulating ionic liquid fuel,*
- *Thanks to the high velocity for the emitted particles and the up to 100µA/cm² sustainable emitted flux, promising thrust measurements have already been obtained showing plenty of room for improvement.*

*These technological progresses are currently integrated into a specific and innovative Ionic Liquid Thruster fully engineered by ION-X targeting a market entry by the end of 2023. **An in-orbit demonstration mission is currently being planned**.*



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