Colloids

A rather unusual form of *electrostatic* electric propulsion

John Stark
Professor of Aerospace Engineering
Queen Mary University of London

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What is Colloid Propulsion?

Ions

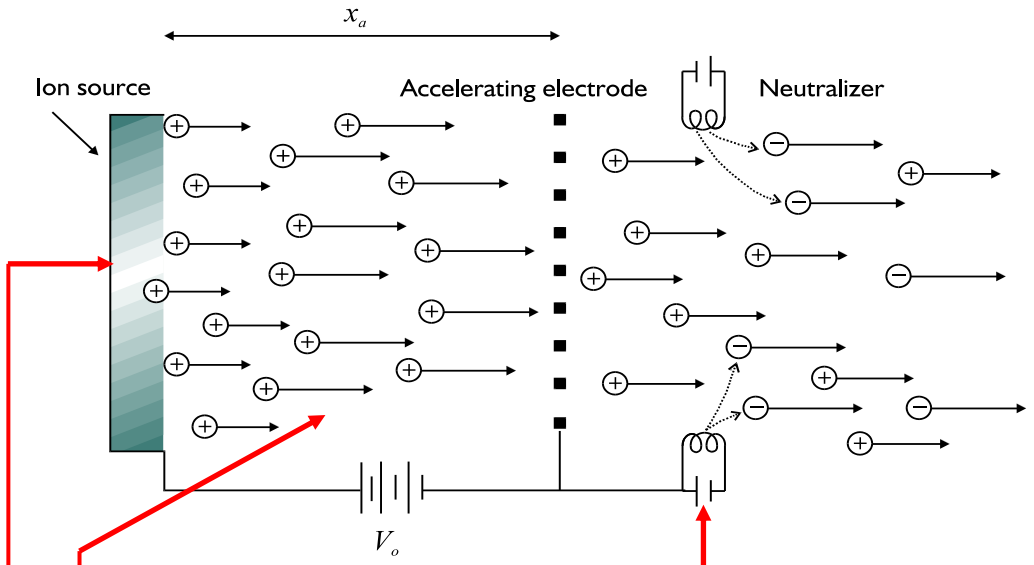
- Direct charging from the liquid phase of ions or droplets

Neutralization

- Negative ***and*** positive propellant species can be generated from the same source

Why is it useful (advantages)?

- Liquid propellant=> Simple(-r) propellant handling
- Ionization efficiency is ***not*** scale dependent=> i) low thrust (eg CubeSats/LISA); ii) Scalable thrust
- Bipolar operation uses all propellant propulsively => high efficiency



Schematic typical of most electrostatic electric propulsion systems

- A source of ions
- An electric field
- A method of ensuring plasma neutrality

Colloid and FEEPS?

- Both based on electro-hydrodynamic atomization but FEEPS requires additional neutralization component (only positive ions)and heating of the “liquid” metal propellant => FEPPS has lower efficiency

Propulsion systems: key parameters:

Thruster

1. Thrust: $T = \dot{m}.V_e$

2. Specific Impulse: $I_{sp} = {}^{V_e}/_{g} = {}^{T}/_{\dot{m}g}$

Mission

1. Total Impulse: $Impulse = \int_o^{T_b} \dot{m} V_e dt$
2. Delta *V*: $\Delta V = V_e.ln\left[\frac{M_0}{M_e}\right]$

System parameters

M_o	Spacecraft mass
g	Surface gravity acceleration
V_e	Exhaust velocity
$\dot{m}$	Propellant mass flow rate
M_e	Mass after fuel burn
T_b	Propulsion system burn time

Electric propulsion parameters

q	Charge on ionized species
m	Mass of charged species
U	Effective accelerating potential

For Electrostatic propulsion:

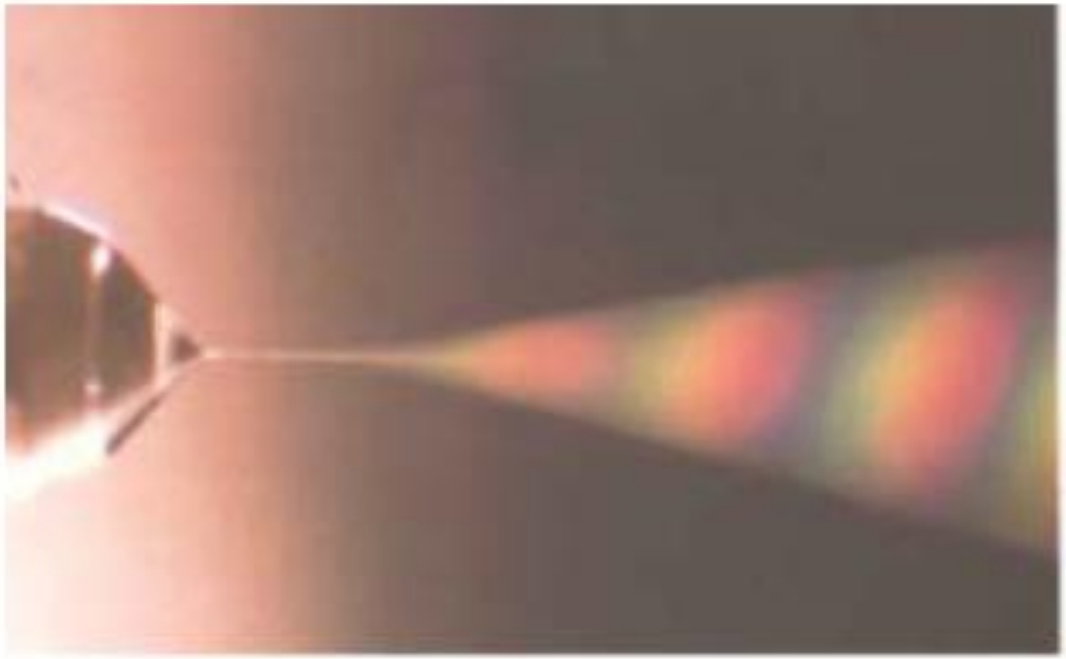
Exhaust velocity is found from balance of potential energy of the charge species and kinetic energy after acceleration -> $V_e = \sqrt{\frac{2q.U}{m}}$

➢ $I_{sp} \propto \sqrt{\frac{q}{m}}$

Electrospray physics:

The Ionization source

Stable Electrospray: “Cone-Jet mode operation”

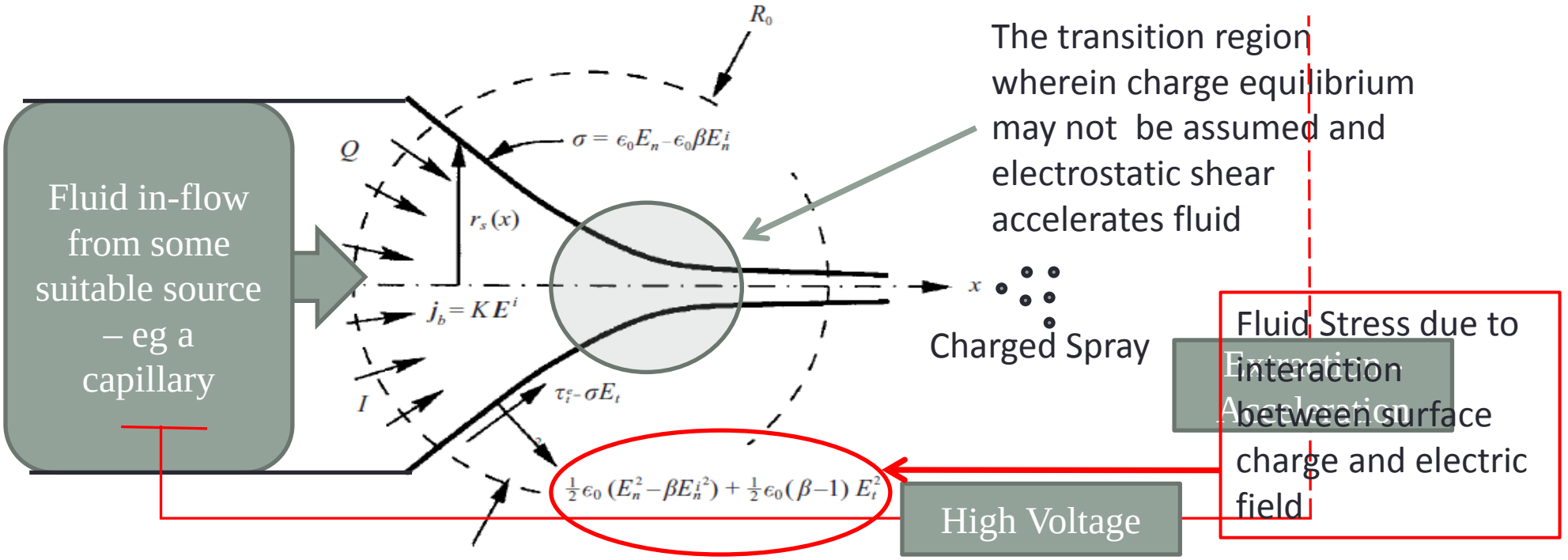


Pantano et al J. Aerosol Sci. **25**,1065 (1994)

Electrospray can generate either ions **or** ions and charged droplets **or** just charged droplets hence:

- Colloid propulsion

Continuous electrospray: the stable Cone-Jet

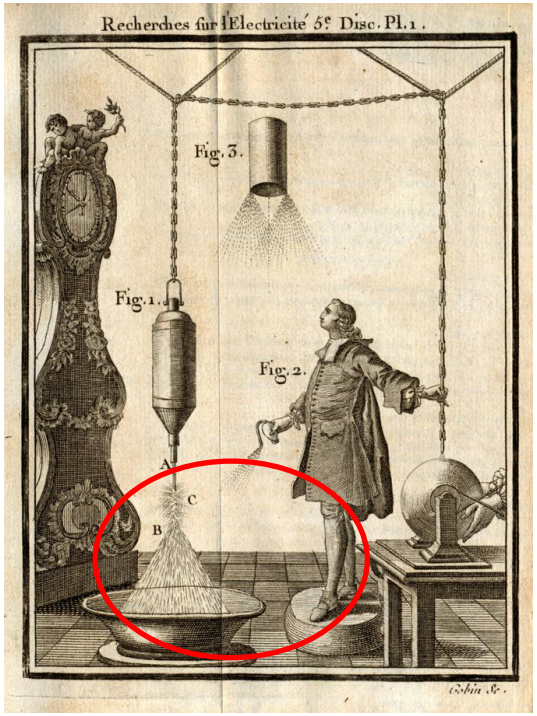


- Analysis and modelling of electrospray process generally based on the Taylor-Melcher leaky dielectric model * although frequent adoption of simplification such as perfect conductivity in fluid.

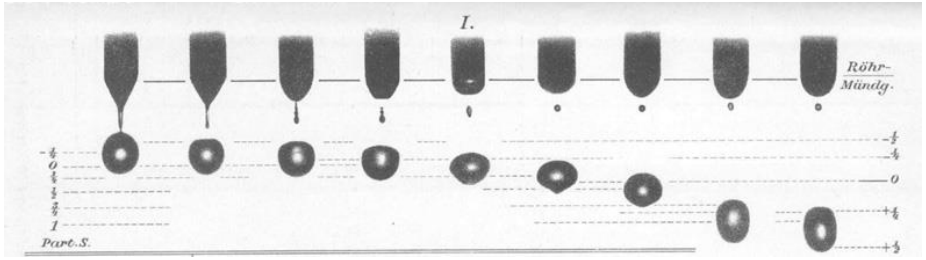
* Saville D. A., Electrohydrodynamics: the Taylor-Melcher leaky dielectric model. Annu. Rev. Fluid Mech., 1997, 29, 27–64

Jets and Charged Jets: a historical perspective

First published work on charged jets was by Abbe Nollet in 1749: breakup at “C” leads to tiny sub-jets

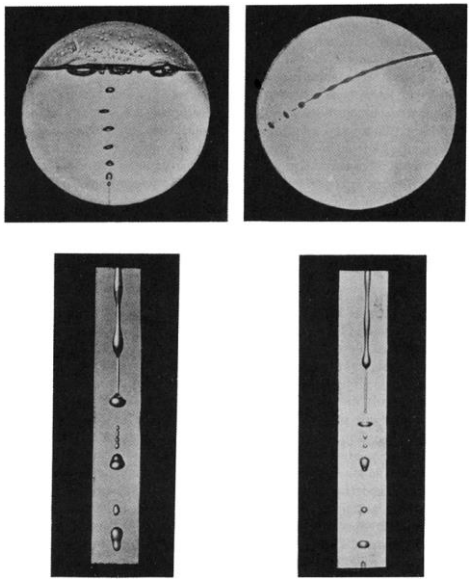


Nollet A 1749 *Recherches Sur les Causes Particuli`eres des Phe´nome`nes E´lectriques* (Paris: les Fre`res Guerin)



Lenard P 1887 *Ann. Phys. Chem.* **30** 209

Jets are always unstable;
First detailed work by Plateau and Lord Rayleigh who identified the breakup is driven by the growth rate of the fastest growing instability – frequently called the Rayleigh-Plateau Instability
Image: Here the fastest growing instability is the axisymmetric ***Varicose*** instability: Rayleigh 1891 Nature 44 249–54



Early systematic study of electrified jets/ electrospray was by Zeleny 1915, 1917

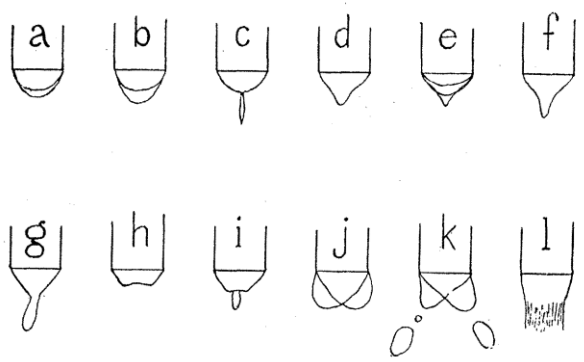


Fig. 3.

Oscillations of meniscus during intermittent discharge.

Zeleny Physical Review 1914, 1917

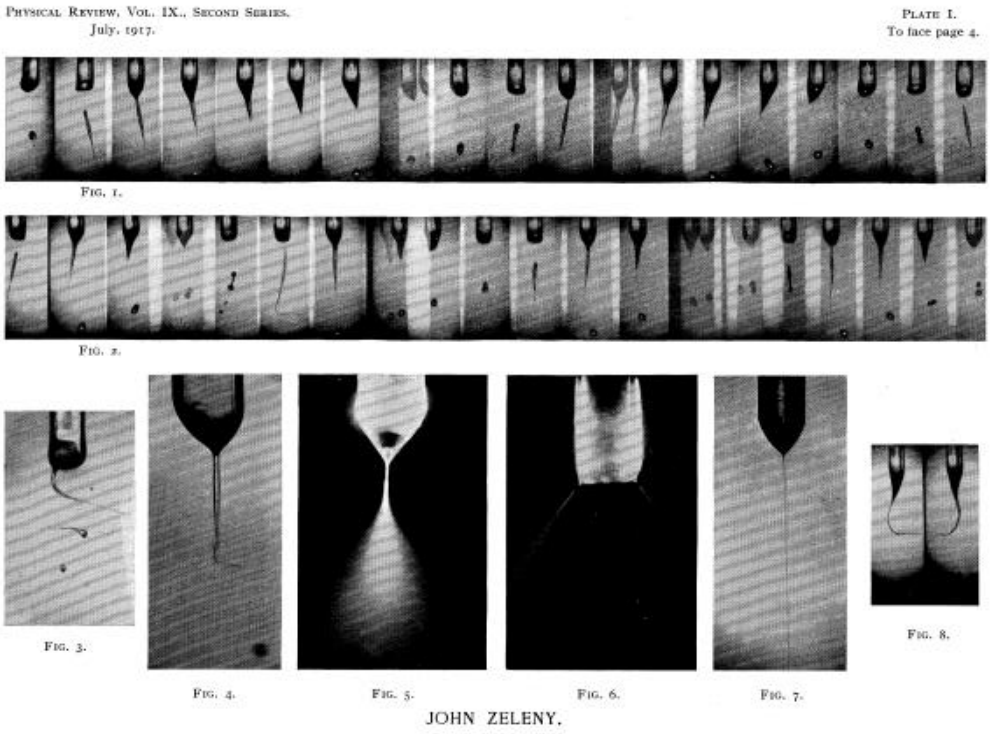


Figure 3 above captures the main modes of *electrospray* without the advantages of modern high speed, high resolution imaging systems!

Electric field increasing

Quiescent modes

Dripping

Meniscus: Semi-spherical.
Drop: simple spherical
(with trailing thread or sibling).

Microdripping

Meniscus: cone/hemispherical.
Drop: small, simple spherical
(in some cases with trailing/leading thread).

Spindle

Meniscus: cone/semi-spherical.
Drop: elongated fragment of
liquid (spindle) (with trailing thread).

Continuous Modes

Cone-jet

Meniscus: cone (linear, concave, convex, skewed)
Jet: simple straight linear.

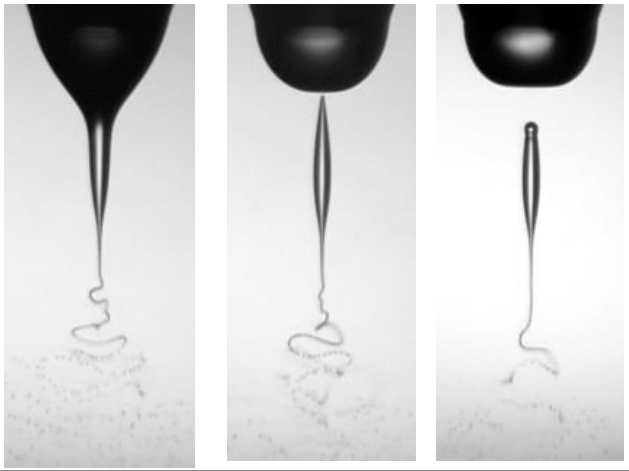
Multijet

Meniscus: flat, with small cones on the rim.
Jet: linear, multiple.

Ramified-jet

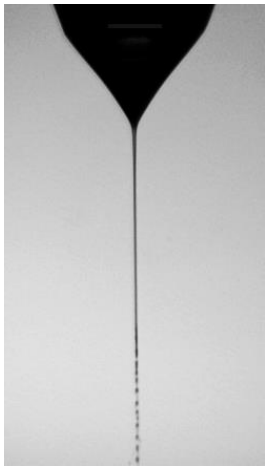
Meniscus: cone.
Jet: linear, ramified in random directions.

Evolution during spindle mode

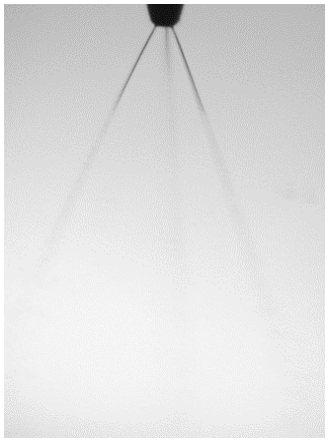


All images curtesy H Xia
PhD thesis QMUL 2018

Cone jet



Multi-jet



Whipping jet

Scaling Laws:

The relationship between spray current ***I*** and flow rate ***Q*** : this depends on the ***mode***

Colloid Thrusters:

- Stable operation requires *Cone-jet* mode
- Accepted scaling law is that associated with *Fernandez de la Mora*[2]:

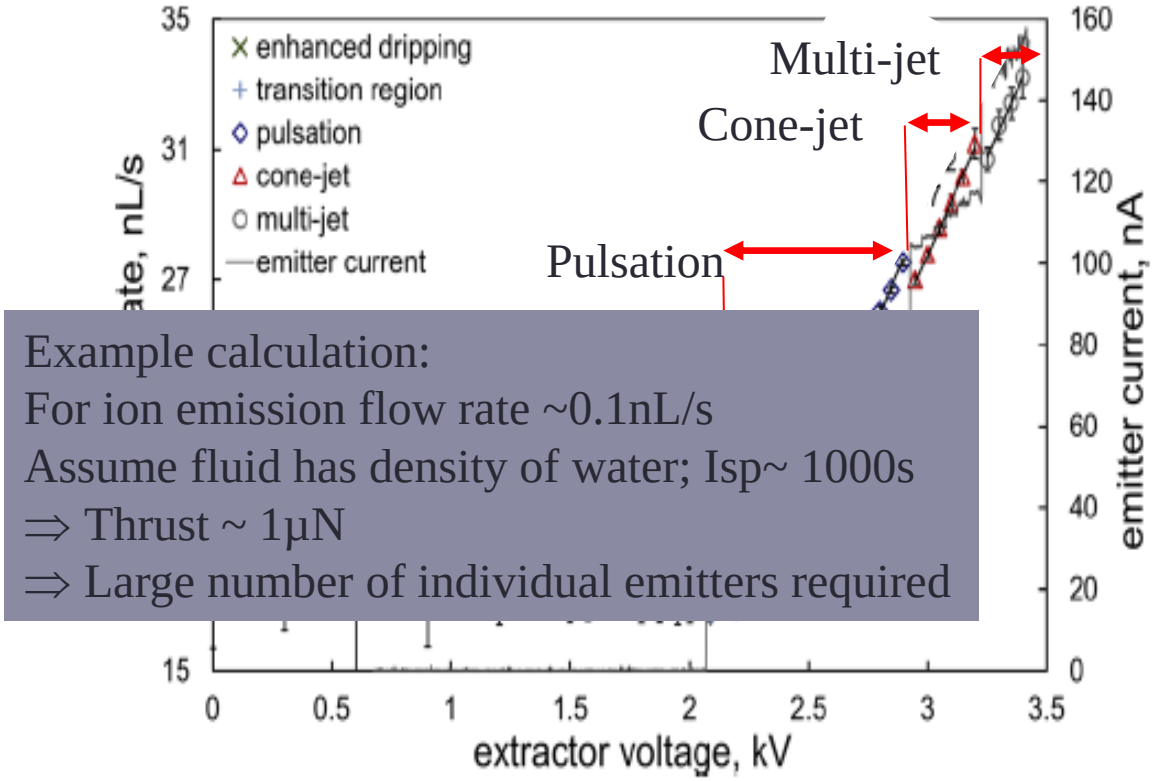
$$I \propto Q^{\frac{1}{2}}$$

Hence:

$$I_{sp} \propto \sqrt{\frac{q}{m}} \propto \sqrt{\frac{1}{Q}}$$

- ➢ Low flow rates for high performance
- ➢ System typically has low thrust

[2]Fernandez de la Mora & Loscertales J.Fluid Mech. (1994) 260, 155-184



Example calculation:
For ion emission flow rate ~0.1nL/s
Assume fluid has density of water; Isp~ 1000s
⇒ Thrust ~ 1μN
⇒ Large number of individual emitters required

Recent result showing influence of voltage on all modes of electrospray[1]

[1]Ryan et al Appl Phys Letts 104, 084101 (2014)

Scaling Laws(cont)

The scaling laws also identify an approximate value for the minimum stable flow rate for a fluid of density ρ having a conductivity σ surface tension γ and permittivity ε for an electrospray system

$$Q_{min} \approx \frac{\gamma \varepsilon}{\rho \sigma}$$

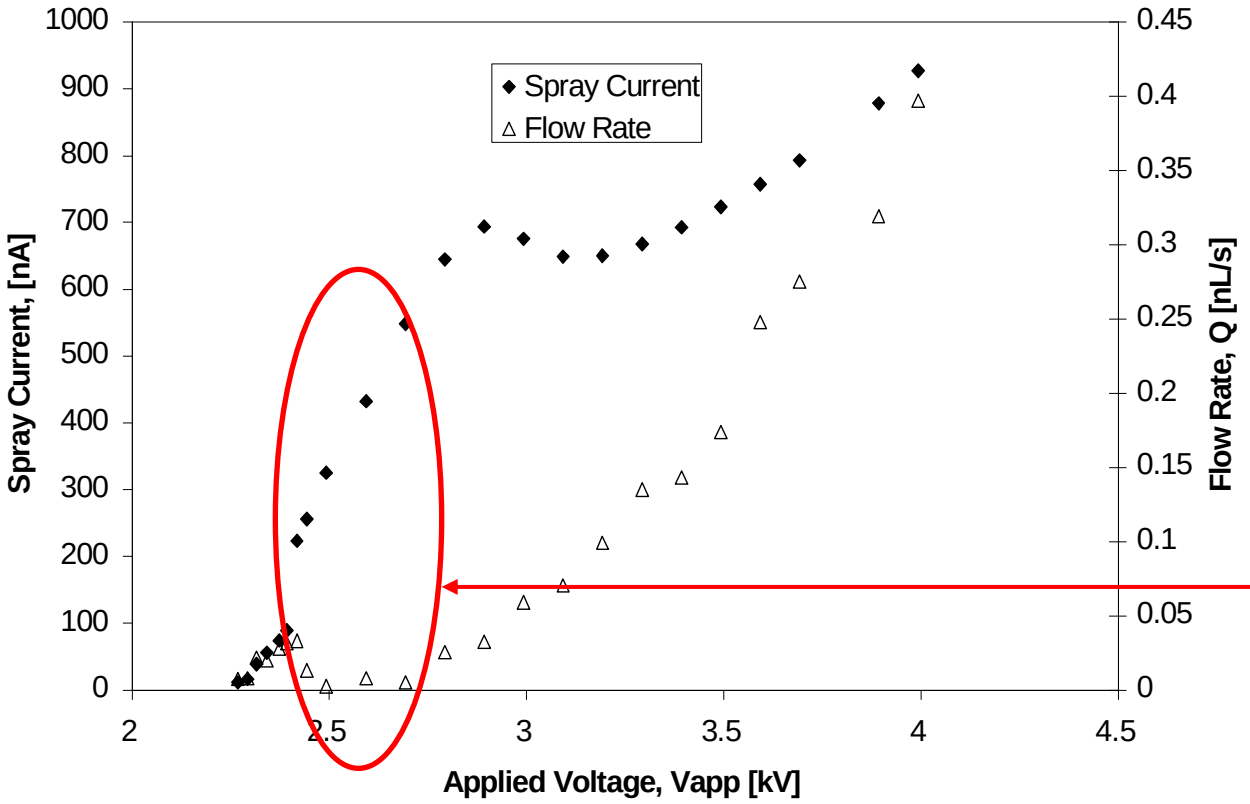
- For high performance a high conductivity liquid is required

- Discovered that with extremely high conductivity liquids the resulting "spray" can contain substantial fraction of pure (molecular) ions –> *high iconicity*
- Suitable liquids identified as *Ionic Liquids* as they combine high conductivity and very low vapour pressure (no evaporation in space). A typical liquid *EMI* BF_4

For *EMI* BF_4 Qmin~20pL/s
Isp~ 1000s
⇒ Thrust ~ 0.2μN

Example behaviour*: EMI BF_4 *average* flow rate vs spray current in vacuum

Note: Flow rate controlled by voltage alone



Ion emitting regime: significantly higher emission current than expected from scaling law

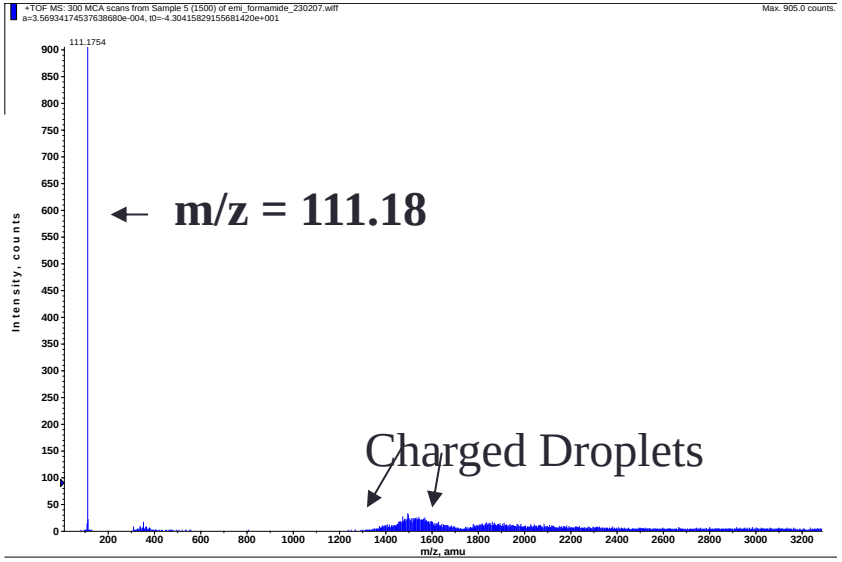
*Stark et al 387th Heraeus Seminar Statics and Dynamics of Electrified Liquids: Droplets, Cones and Jets 2007

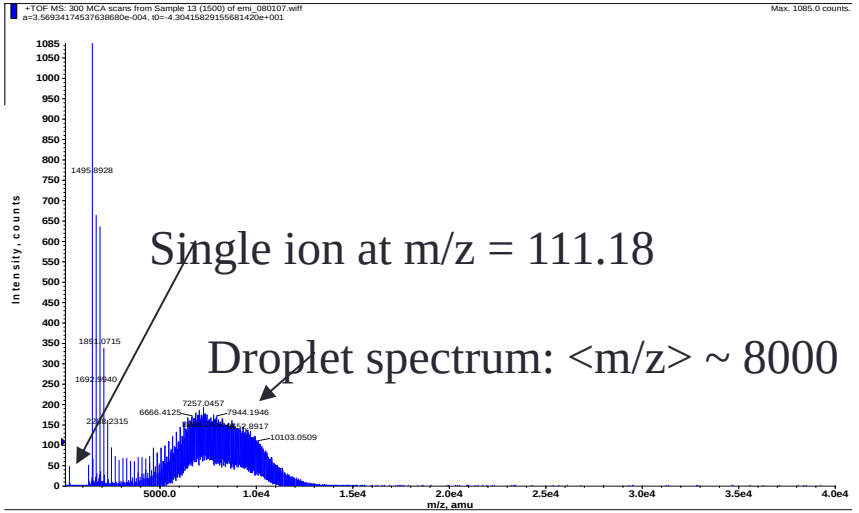
Colloid Thruster Implications

- The average specific charge is dependent upon the operating conditions, such as voltage and any upstream pressure
- Specific charge is dominated by the need to maintain a stable flow at very low flow rate
- This requires a system with high hydraulic impedance

Options:

1. An externally wetted needle or a porous needle
2. Internal capillary flow with high impedance such as achieved with high aspect ratio (length/diameter)





Colloid system realizations

Option 1: Externally wetted/shaped porous needle

- This development has been led by MIT who work with Busek Ltd and have spin out company Accion Systems Ltd
- Basic concept: porous emitter structure
- Pore size gradient -> capillarity self wetting
- Structure of emitter shape critical
- Produce very high iconicity
- Single electrode structure to achieve Isp

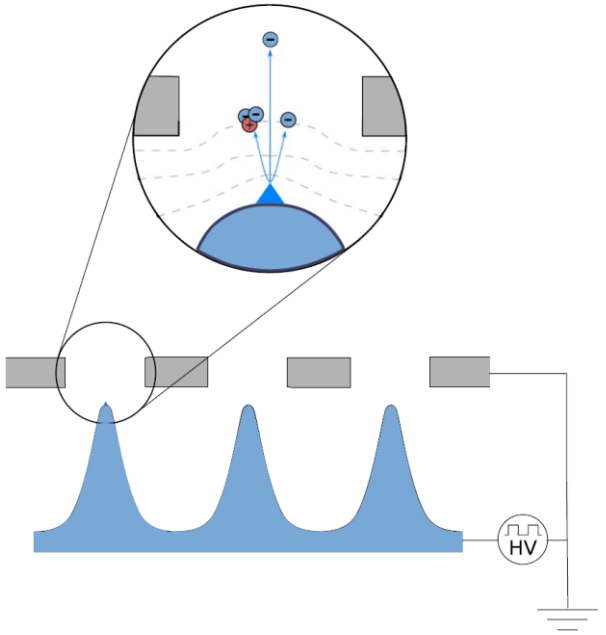
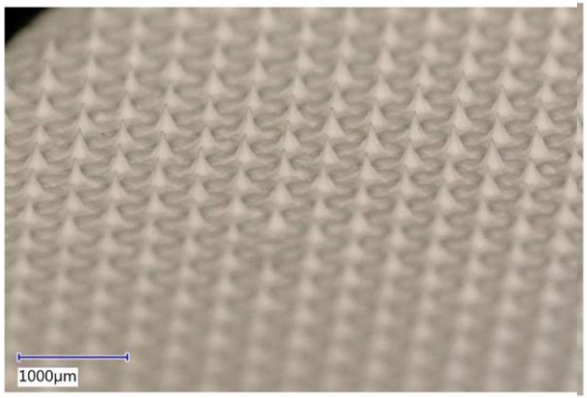


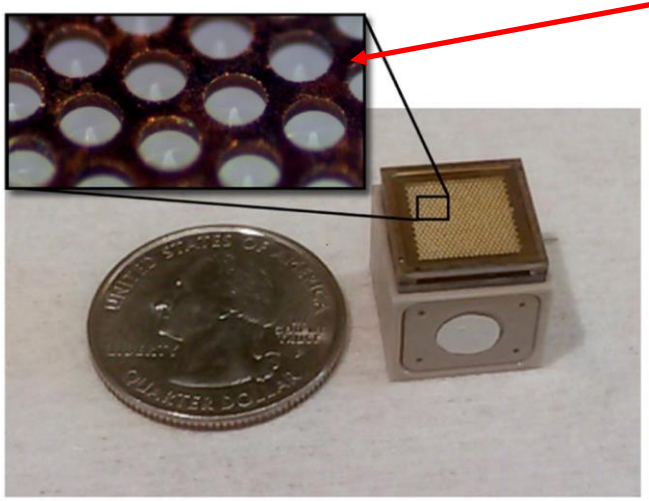
Fig. 1 Electrospray principle with charged particle extraction from menisci on top of porous emitter structures.

Krejci et al J. Spacecraft & Rockets 2017

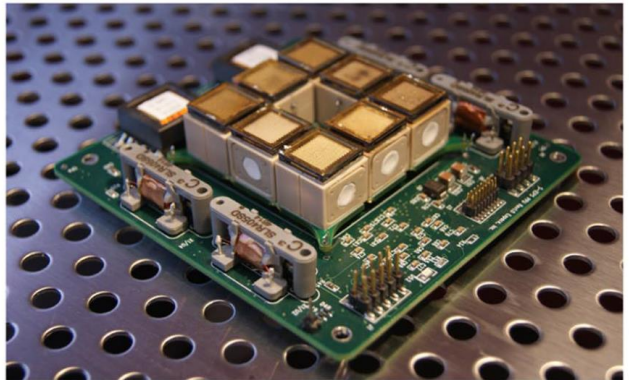
Option 1: Externally wetted/shaped porous needle (cont)



Porous needle array



Extractor grid: voltage will control extraction conditions and Isp



Krejci et al J. Spacecraft & Rockets 2017

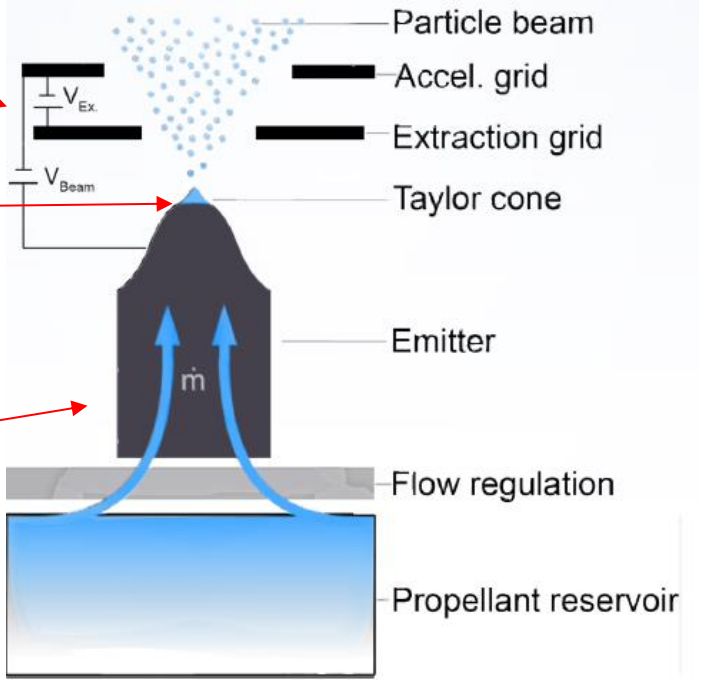
Option 1: Externally wetted/shaped porous needle (cont.)

In this design a dual grid is used: higher flow rate/lower specific charge

Formation of needle tip shape is critical to operation: the tip can have pores at different angles -> beam divergence

Porous needle with pore size gradient to use capillarity to feed the needle

Busek design for 100µN

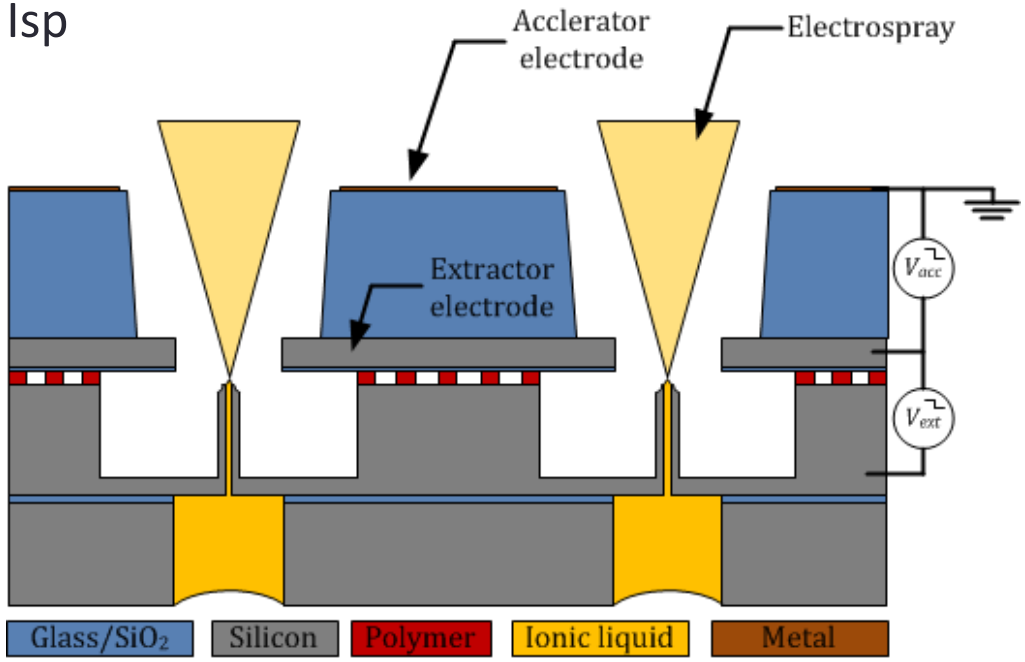


Colloid system realizations

Option 2: Internally wetted capillary system

- Approach has been led by QMUL group
- Capillary flow leads to higher flow rate and lower specific charge than in the porous systems

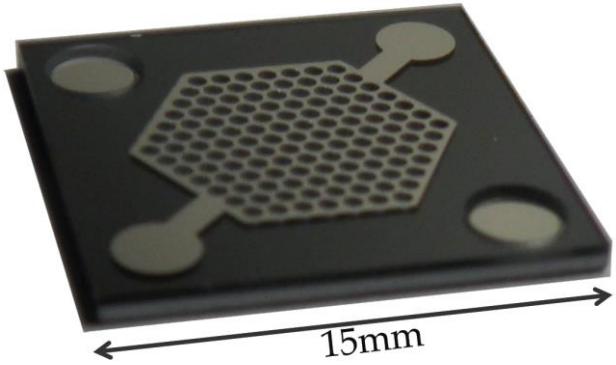
➢ Require dual electrode system to achieve Isp

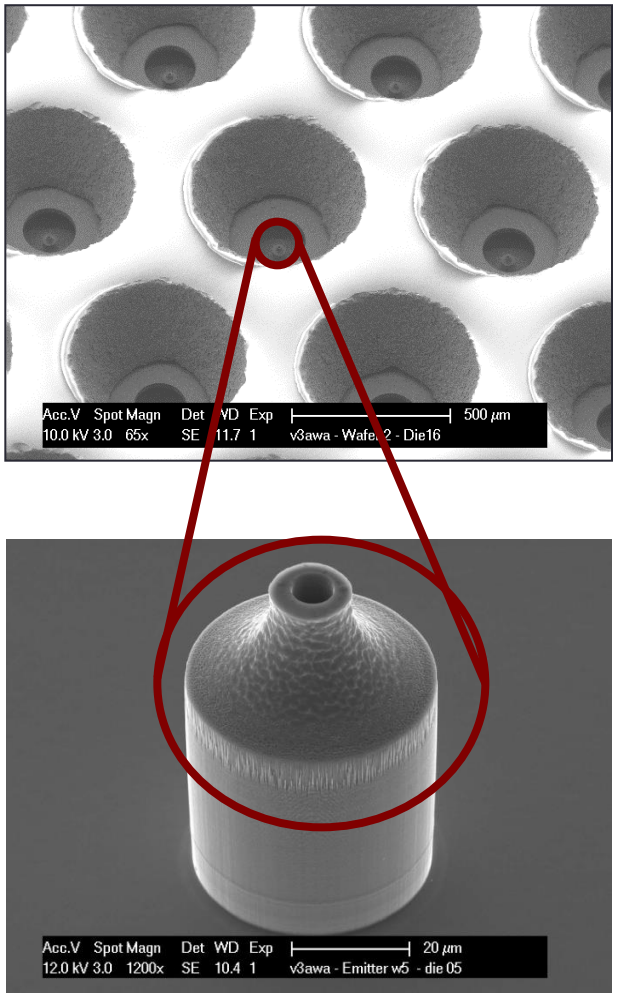


Internally wetted capillary system (cont)

- In this realization the emitters are manufactured in silicon using deep reactive ion etching techniques
- Major challenge achieving the high hydraulic impedance simply through the capillary aspect ratio

Images from research carried out under FP7 Programme

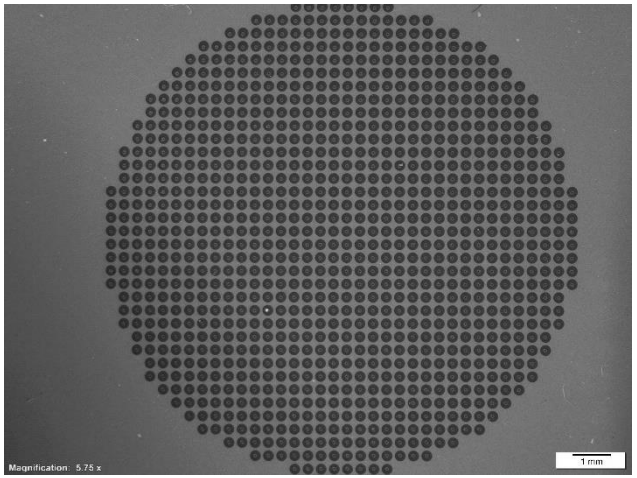




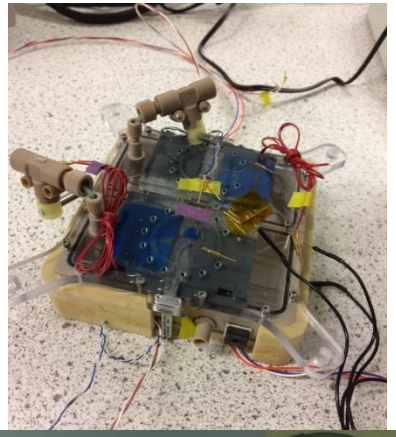
Ryan et al IEPC 2013 – 127 (2013)

Internally wetted capillary system (cont)

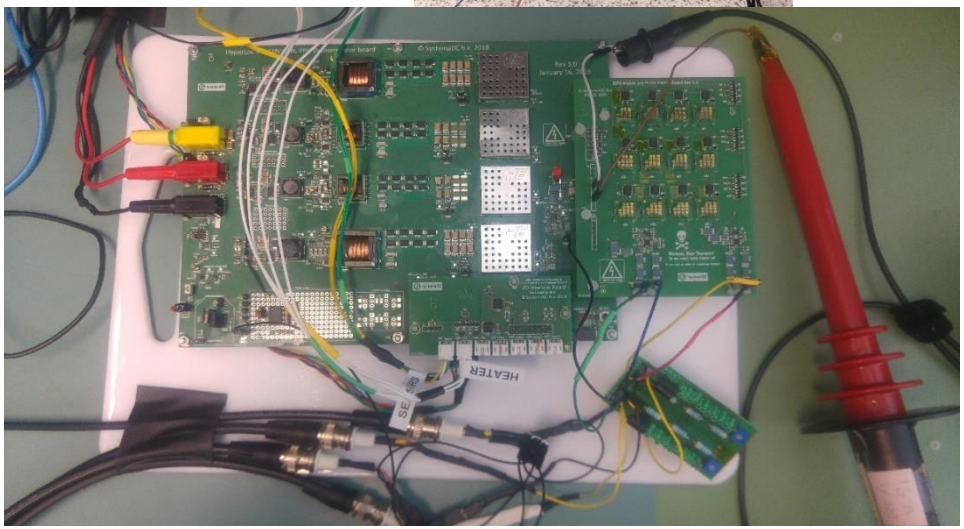
- Current project: HiperLoc-EP (within the EPIC project) is focused on cost reduction to become a disruptive electric propulsion technology
- Performance: >500µN at Isp>1000s and η>50%



Colloid thrust head sized for 500µN



BBM Integrated propellant supply & feed system



BBM Integrated PPU

External wetted: Porous

Advantages

- High specific charge -> high specific impulse
- Simple flow control
- Single electrode for acceleration and extraction

Disadvantages

- High power
- Inflexible regarding Isp
- Electrochemical degradation
- In-efficiency: beam divergence
- Complex manufacturing
- Cost

Internal flow: Capillary

Advantages

- Higher thrust per emitter
- Potential for integration at sub-system level
- Flexibility: extraction/acceleration are independent
- Low electrochemical degradation
- Low power: optimization possible
- Cost

Disadvantages

- Flow control complexity
- Limited Isp
- Beam specific charge poly-diversity

Conclusions and Opportunities

- **Colloid systems performance:**
  - The nature of the required power is DC high voltage, highly efficient through DC:DC converters
  - High performance:
    - Isp typically > 1000s: this can be tuned if required to specific mission requirements
    - Thrust is scalable from 10's µN to 100's mN at the same high efficiency
  - No magnetic field required
  - Benign "green" propellants
  - Potentially low cost
- **Opportunities**
  - Particular suited to CubeSat type missions
    - Compact
    - Low power
  - Manufacturing approach could make it suitable for constellations of micro/small satellites
  - Low thrust level appropriate for formation flying missions such as LISA

Thank You

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Thank You