Electrospray from Magneto-electrostatic Instabilities

December 9, 2015

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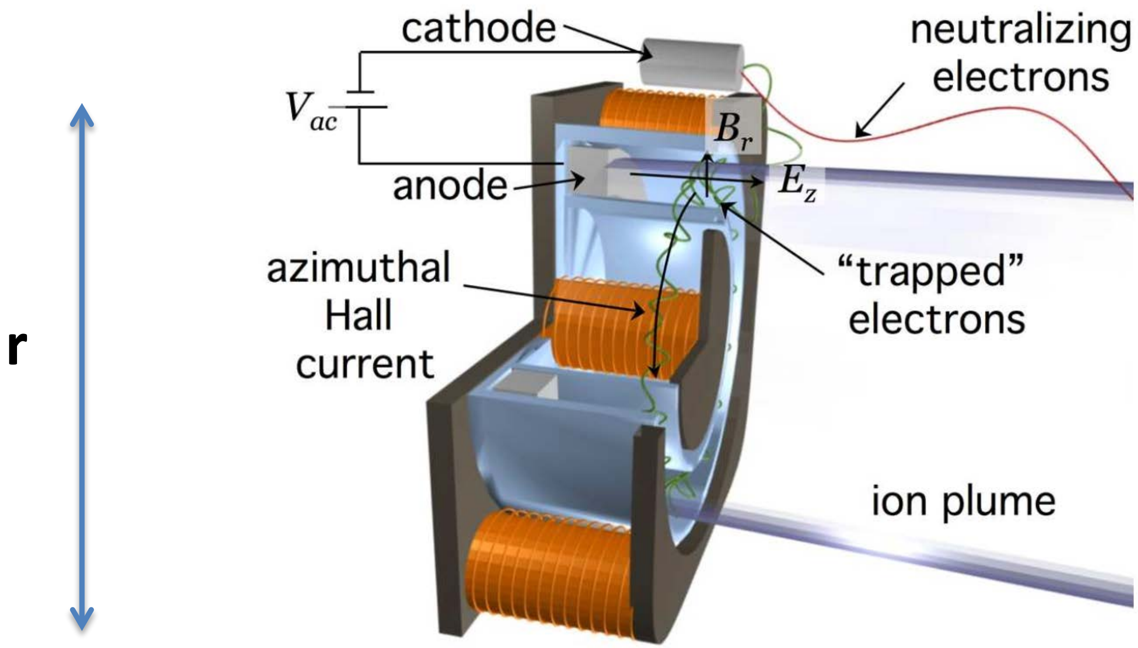
Operational Satellites with Electric Propulsion

All Spacecraft Employing EP = 236
Spacecraft Employing Aerojet EP = 158

05 / 20 / 10

AEROJET

Yale MichiganTech ILLINOIS

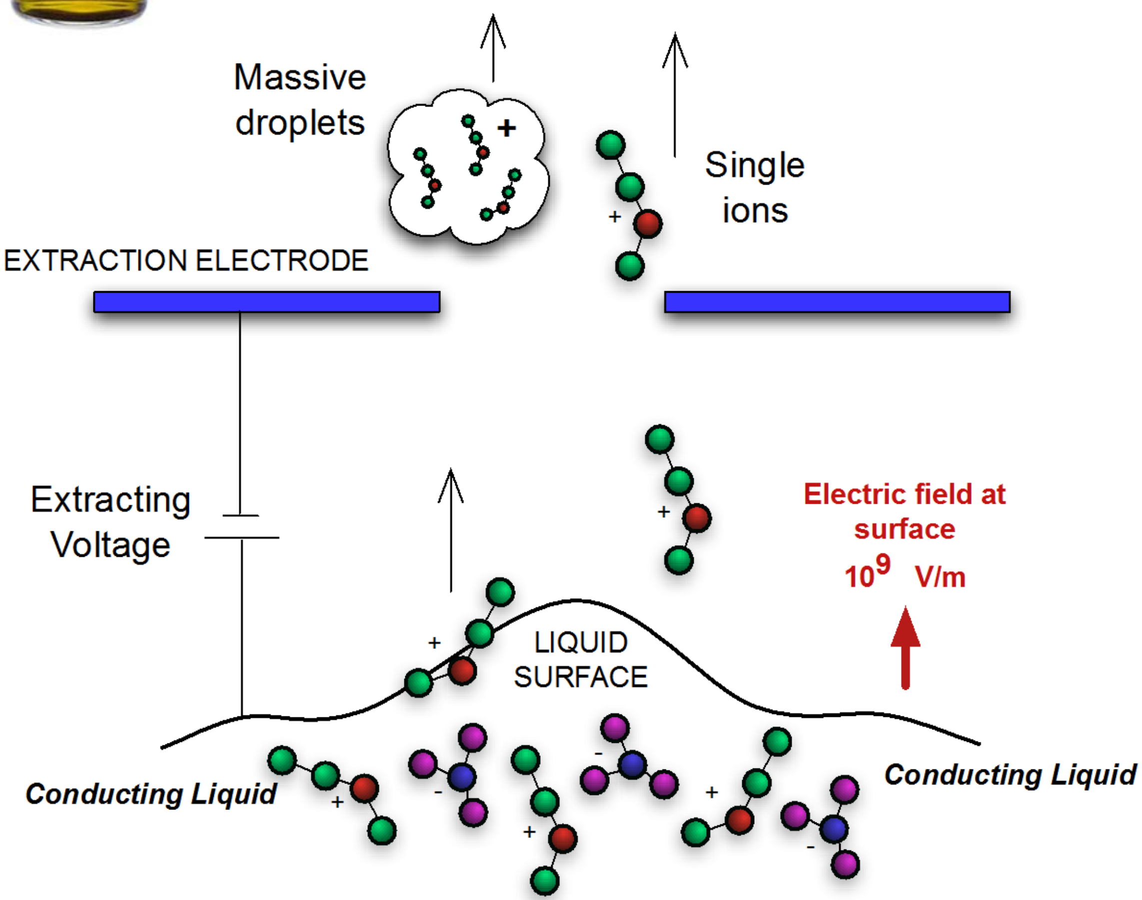


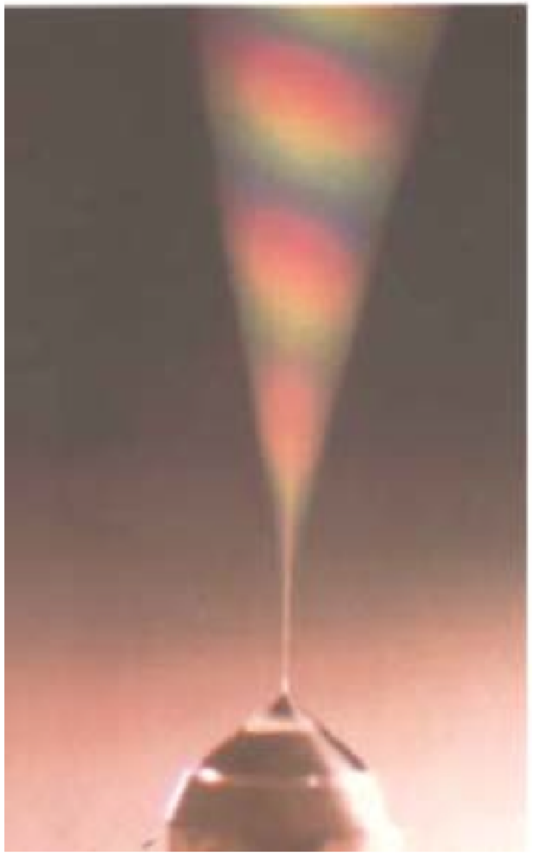
Gas density: $$\lambda = \frac{1}{n\sigma} \Rightarrow n \propto \frac{1}{r}$$

$$\frac{\text{Amount of erosion}}{\text{Amount of material}} \propto \frac{\text{Area}}{\text{Volume}} = \frac{r^2}{r^3} = \frac{1}{r}$$

Magnetic field: $$r_L = \frac{mv_\perp}{|q|B} \Rightarrow B \propto \frac{1}{r}$$

Electrospray: plasma in a bottle

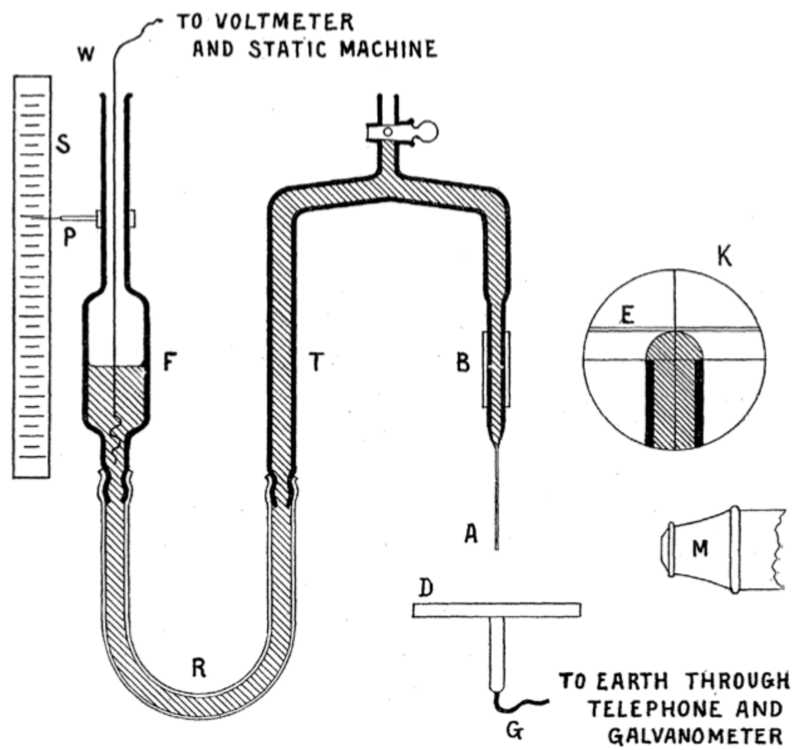




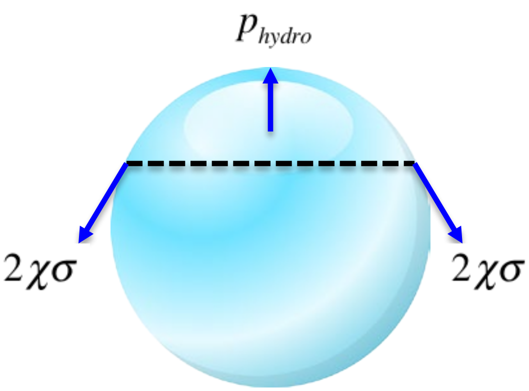
Jean-Antoine Nollet – **1750**:

“a person, electrified by connection to a high-voltage generator, would not bleed normally if he were to cut himself; blood would spray from the wound.”

Zeleny, J., "The electrical discharge from liquid points, and a hydrostatic method of measuring the electric intensity at their surfaces," *Physical Review,* **3**(2), **1914**, 69-91.



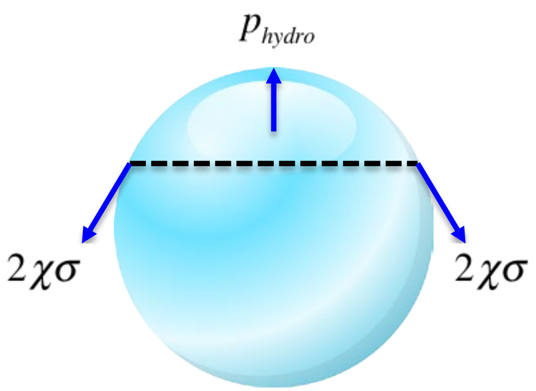
Neutral Fluid



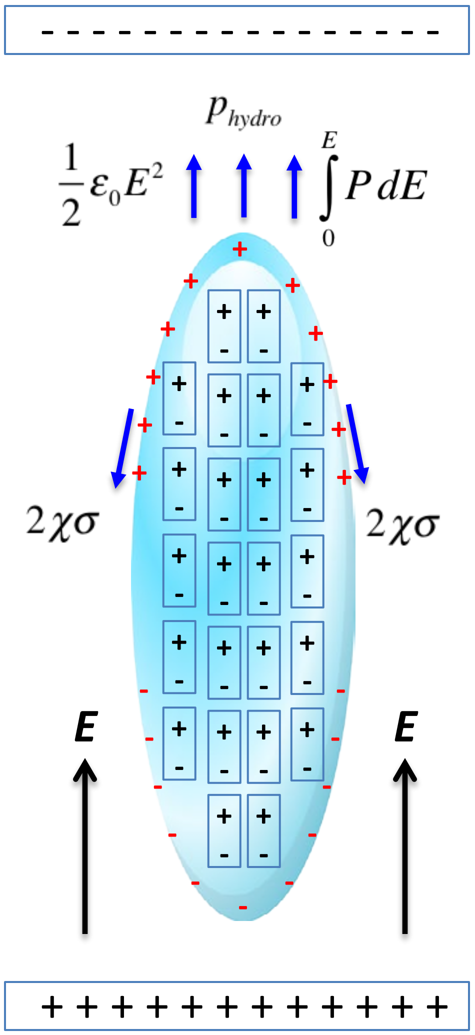
Surface tension is balanced by fluid pressure

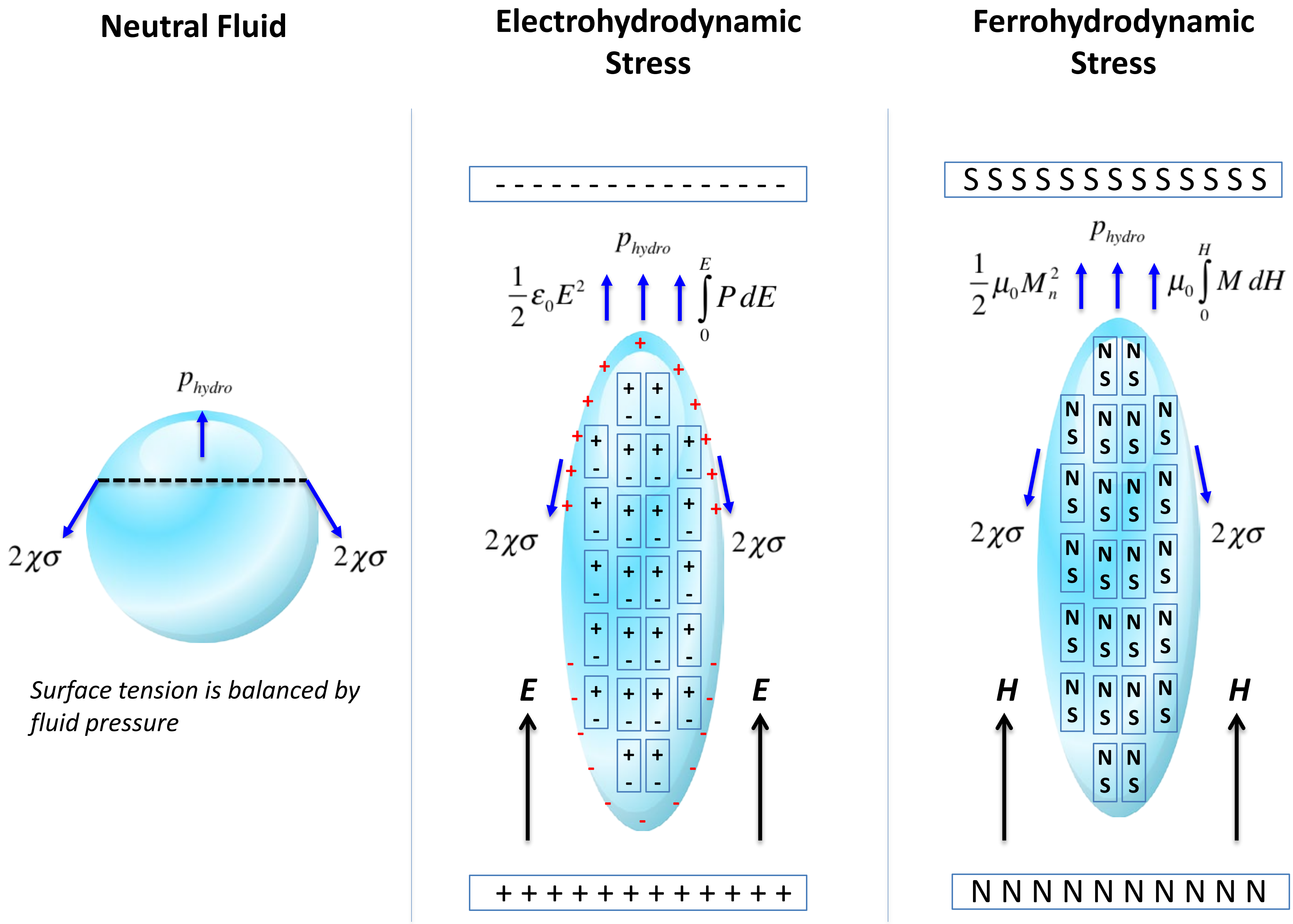
Neutral Fluid

Electrohydrodynamic Stress



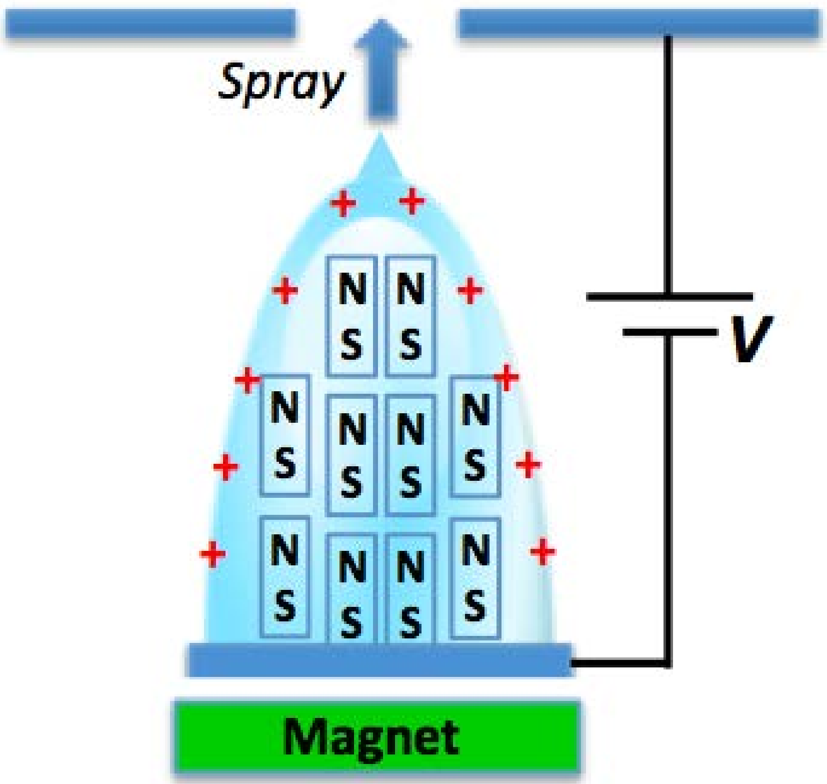
Surface tension is balanced by fluid pressure

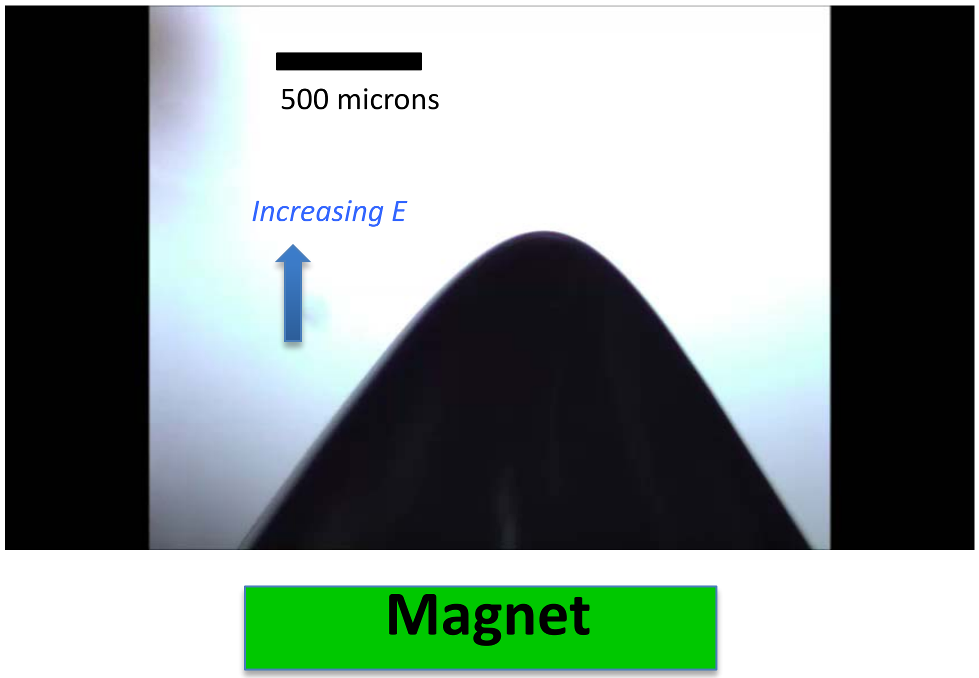




Neutral Fluid
Electrohydrodynamic Stress
Ferrohydrodynamic Stress
p_{hydro}
$2\chi\sigma$
$2\chi\sigma$
Surface tension is balanced by fluid pressure
- - - - - - - - - - - - - - - - -
p_{hydro}
$\frac{1}{2}\varepsilon_0 E^2$
$\int_0^E P\,dE$
$2\chi\sigma$
$2\chi\sigma$
E
E
+ + + + + + + + + + + + +
S S S S S S S S S S S S S
p_{hydro}
$\frac{1}{2}\mu_0 M_n^2$
$\mu_0 \int_0^H M\,dH$
$2\chi\sigma$
$2\chi\sigma$
H
H
N N N N N N N N N N

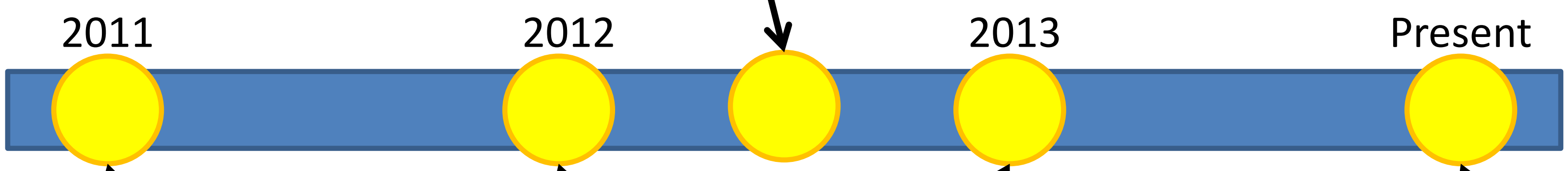
Explore new fluid mechanics of combined ferro- and electrohydrodynamic spray emission





New material: Ionic liquid ferrofluid

Collaboration between Michigan Tech and The University of Sydney



Huang and Wang [7]:
EMIM-ethylsulphate with $CoFe_2O_4$

Jain et al [6]:
EAN with Fe_2O_3
EMIM-Ac with Fe_2O_3
EMIM-SCN with Fe_2O_3

EAN with Sirtex nanoparticles

$EMIM\text{-}NtF_2$
Sulfolane + EAN
Triglyme
Glycerol
(all with Sirtex MNPs)

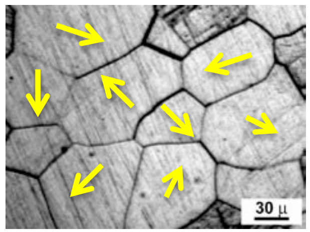
[6] Jain, N. et at., Stable and Water-Tolerant Ionic Liquid Ferrofluid. Applied Materials and Interfaces 2011 (3): p. 662-667

[7] Huang, W. and Wang, X., Stuy on the properties and stability of ionic liquid-based ferrofluids. Colloid Polym Sci, 2012 290: p. 1695-1702

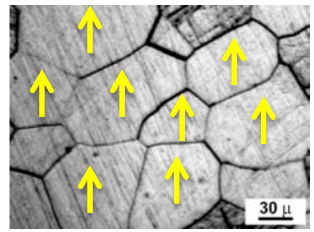
How to make a Ferrofluid

Melting a Ferromagnetic Substance Doesn't Work:

T ~ Room Temp
No applied field
$M_{net} = 0$

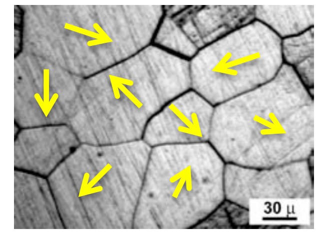


T ~ Room Temp
Applied Field
$M_{net} > 0$



H

T > Curie Temp
Applied Field
$M_{net} \sim 0$

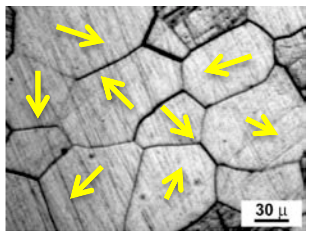
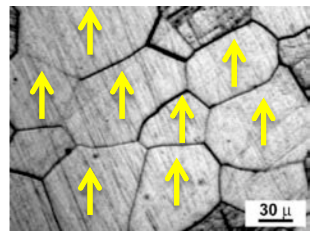
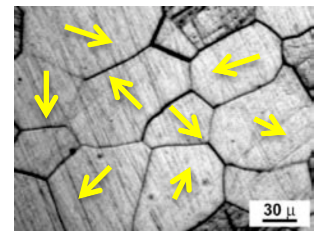


H

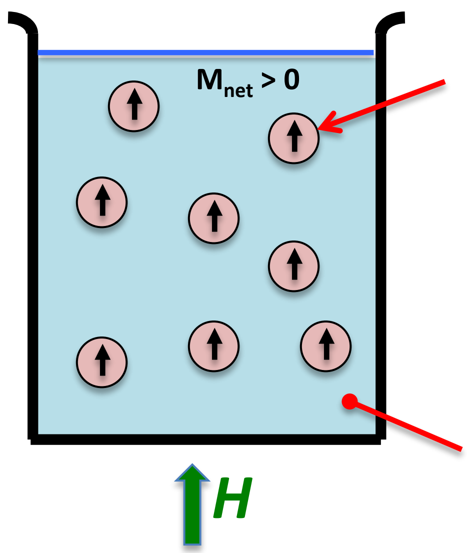
$T > T_{lliquid}$
$M_{net} = 0$

H

How to make a Ferrofluid

	T ~ Room Temp No applied field $M_{net} = 0$	T ~ Room Temp Applied Field $M_{net} > 0$	**T > Curie Temp** Applied Field $M_{net} \sim 0$	$T > T_{lliquid}$ $M_{net} = 0$
Melting a Ferromagnetic Substance Doesn't Work:				
		H	H	H

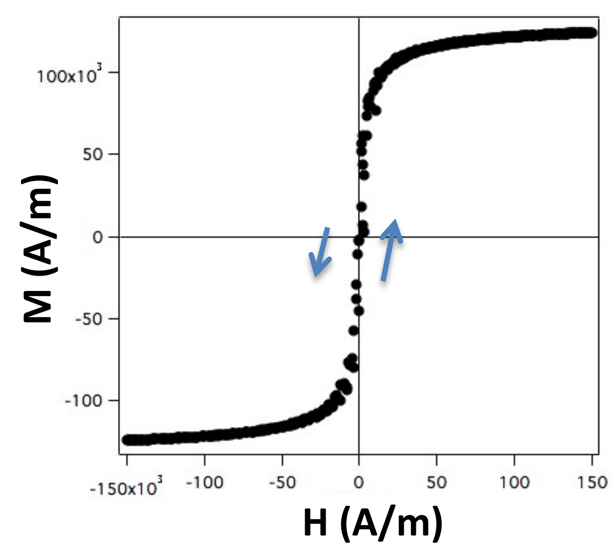
A Ferrofluid is a Superparamagnetic Colloid:



Solid-state ferromagnetic particles small enough to contain only a single magnetic domain (10s of nm)

Carrier liquid

Because the particles are free to rotate
The M-H curve does not display hysteresis



Ionic liquid ferrofluid: a truly magnetized plasma

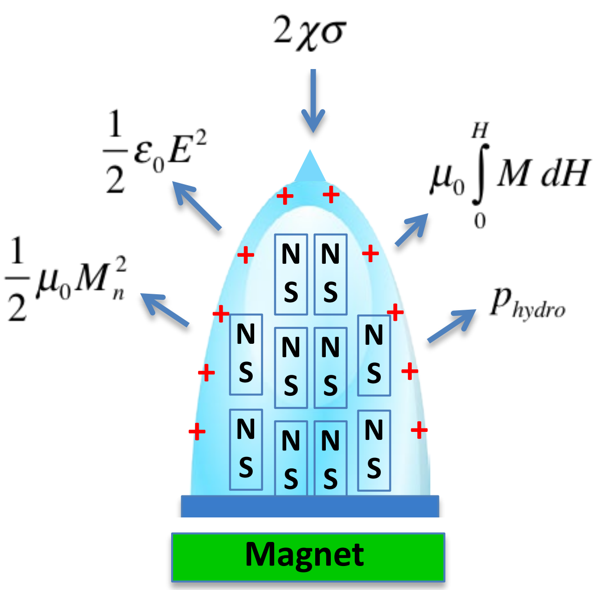
Magnetohydrodynamics	Electrohydrodynamics	Ferrohydrodynamics
$\rho \frac{\partial \mathbf{v}}{\partial t} = \mathbf{j} \times \mathbf{B} - \nabla p$	$\rho \frac{\partial \mathbf{v}}{\partial t} = q\mathbf{E} - \frac{1}{2} E^2 \nabla \varepsilon - \nabla p$	$\rho \frac{\partial \mathbf{v}}{\partial t} = \mu_0 M \nabla H - \nabla p$
Lorentz Force	Coulomb Force	Kelvin Force

Momentum: $$\rho \frac{\partial \mathbf{v}}{\partial t} = \mathbf{j} \times \mathbf{B} + q\mathbf{E} - \frac{1}{2} E^2 \nabla \varepsilon + \mu_0 M \nabla H - \nabla p$$

Quasi-static Maxwell: $$\nabla \times \mathbf{H} = \mathbf{0} \qquad \nabla \cdot \mu \mathbf{H} = \mathbf{0} \qquad \nabla \times \mathbf{E} = \mathbf{0} \qquad \nabla \cdot \varepsilon \mathbf{E} = \mathbf{0}$$

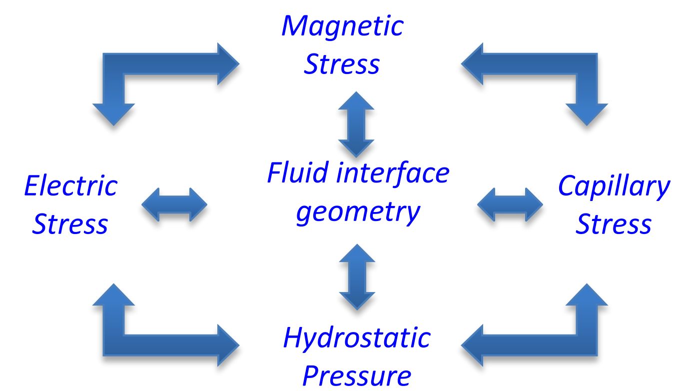
Young-Laplace: $$p_{hydro} + \mu_0 \int_0^H M \, dH + \frac{1}{2} \varepsilon_0 E^2 + \frac{1}{2} \mu_0 M_n^2 = 2\chi\sigma$$

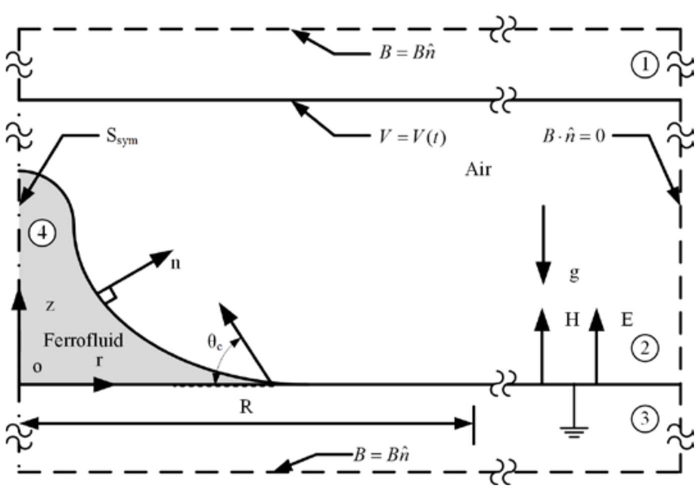
Determine Critical Fields for Spray Onset



Fluid meniscus geometry is non-linear equilibrium

$$p_{hydro} + \mu_0 \int_0^H M\,dH + \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2}\mu_0 M_n^2 = 2\chi\sigma$$



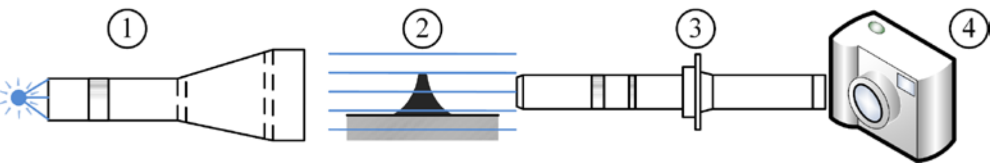


Numerical Simulation of Ferrofluid Droplet

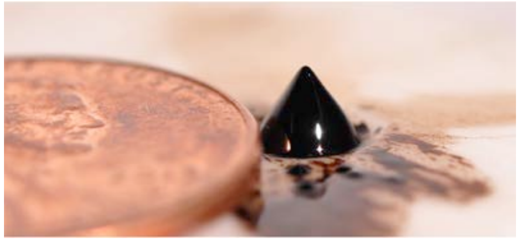
- COMSOL Microfluidics with electromagnetic stress
- Two-phase transient flow with moving mesh (ALE)
- Experimentally determined M-H characteristic for fluid
- Experimentally determined fluid-solid contact angle

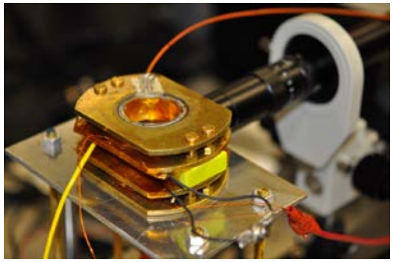
Numerical Model Validation

Collimated Backlight Imager

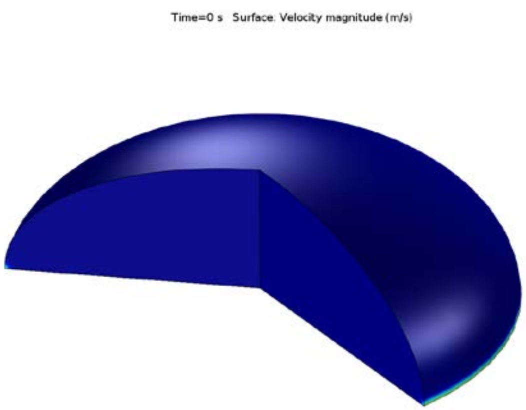


Droplet on Flat Plate in Helmholtz Coil

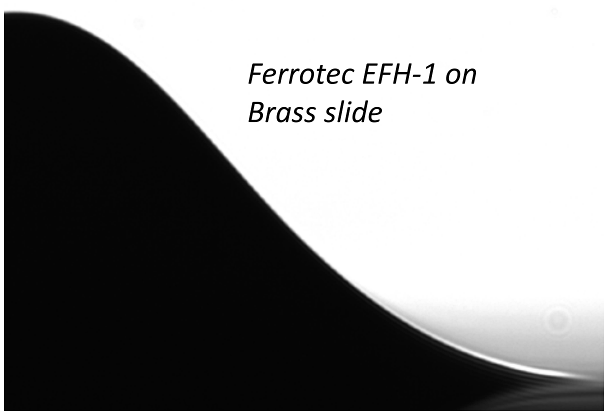




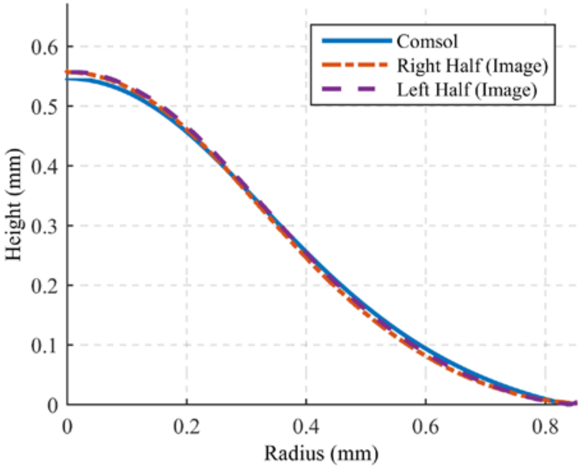
Transient Droplet Dynamics



Silhouette Image



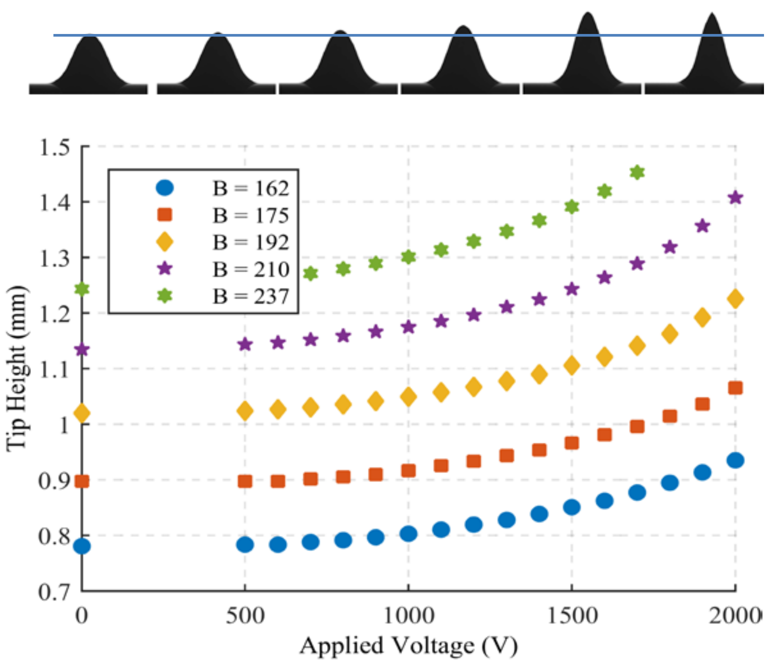
Model Validation



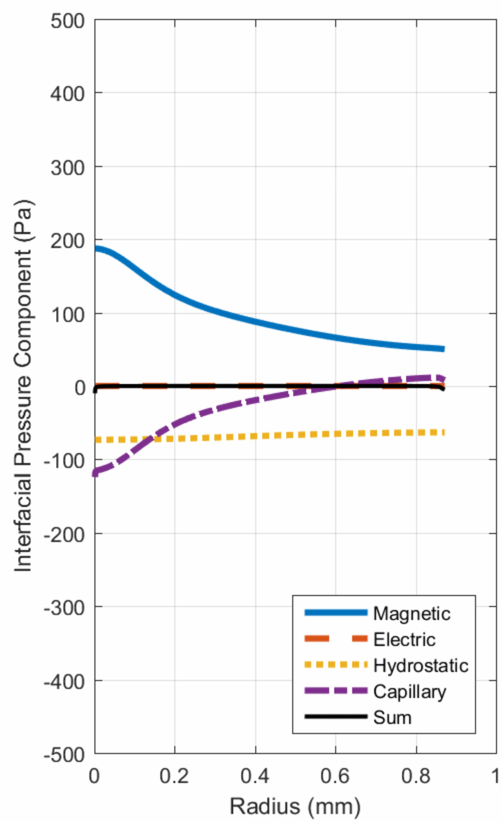
Interfacial Magneto-electrostatic Stress

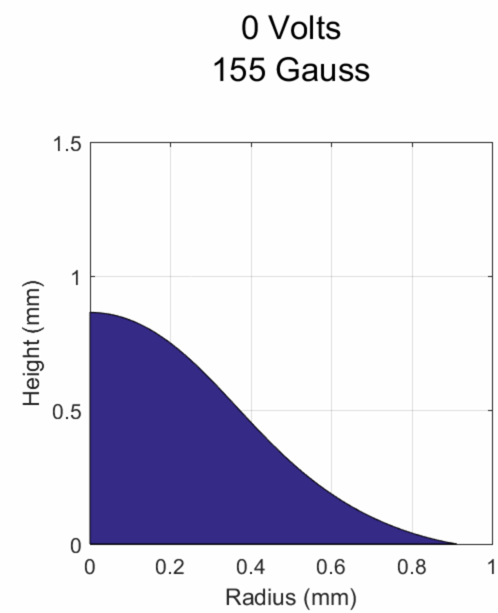
$$p_{hydro} + \mu_0 \int_0^H M\,dH + \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2}\mu_0 M_n^2 = 2\chi\sigma$$

Experimental Silhouette Images



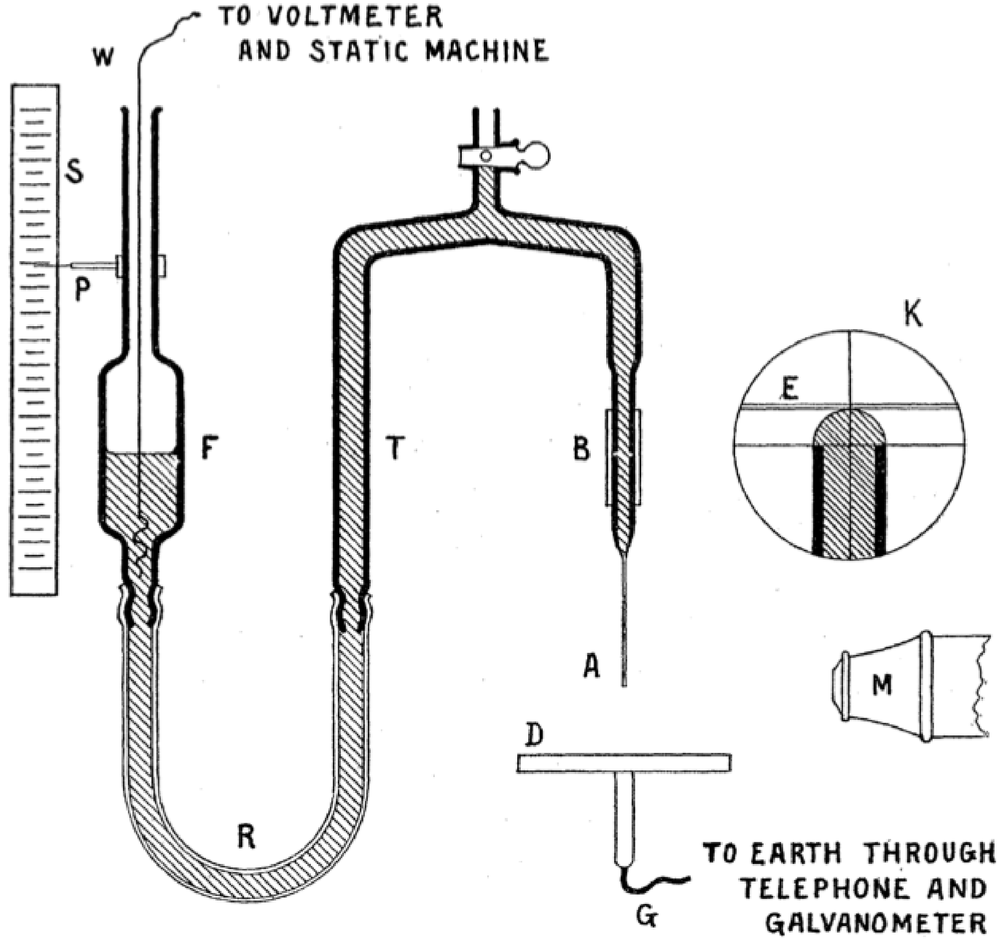
Numerical Simulation





Compare with Established Theory: Capillary Electrospray

Zeleny, J., "The electrical discharge from liquid points, and a hydrostatic method of measuring the electric intensity at their surfaces," *Physical Review,* **3**(2), 1914, 69-91.



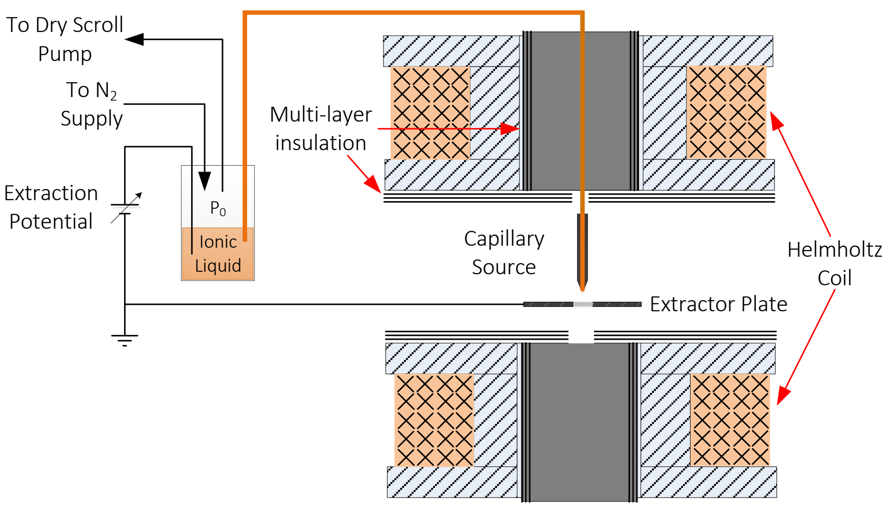
Capillary Studies: Motivation and Approach

Existing Electrospray Theory (over 400 citations):

Fernandez de la Mora, J., and Loscertales, I.G., "The current emitted by highly conducting Taylor cones," J. Fluid Mech. 260, 155-184, 1994.

$$I \sim \sqrt{\frac{\gamma Q K}{\varepsilon}}$$

Surface tension → γ; *Flow rate* → Q; *Conductivity* → K; *Permittivity* → ε; *Spray current* → I



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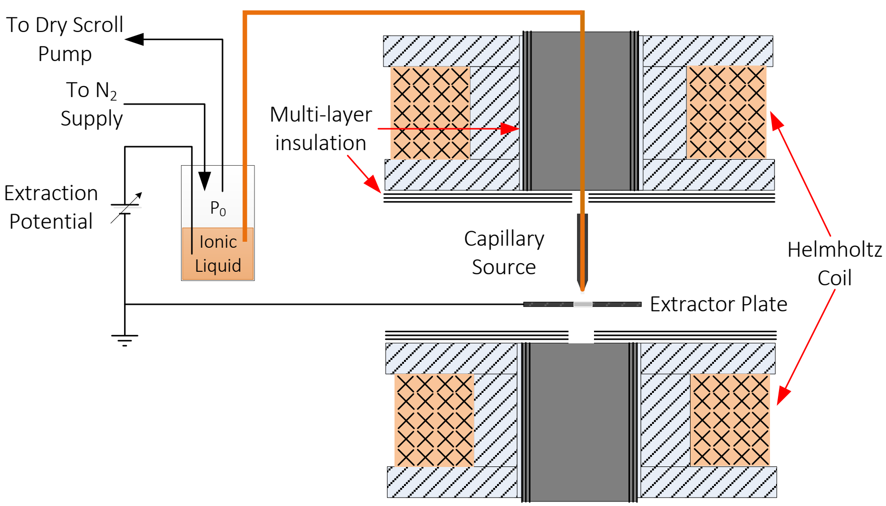
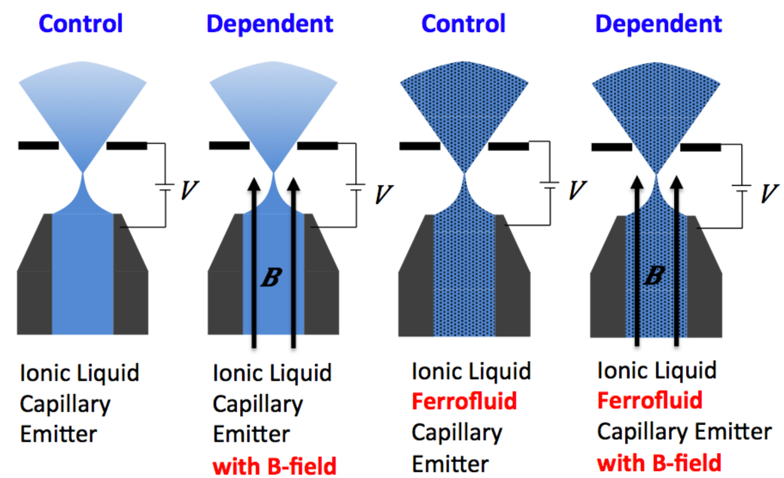




Sprayed in atmosphere (Sulfolane + 0.1% EAN, Sulfolane + 1% EAN, Sulfolane + 10% EAN)

Sprayed in vacuum (EMIM-NTf2)

Ferrofluid base	Sulfolane + 0.1% EAN	Sulfolane + 1% EAN	Sulfolane + 10% EAN	EMIM-NTf2
Conductivity (S/m)	0.012	0.033	0.324	0.57

Ferrofluids synthesized by University of Sydney Key Centre for Polymers and Colloids (Hawkett and Jain) by stabilizing ~ 50-nm-diameter maghemite particles supplied by Sirtex Medical, Ltd.

Capillary Spray Results

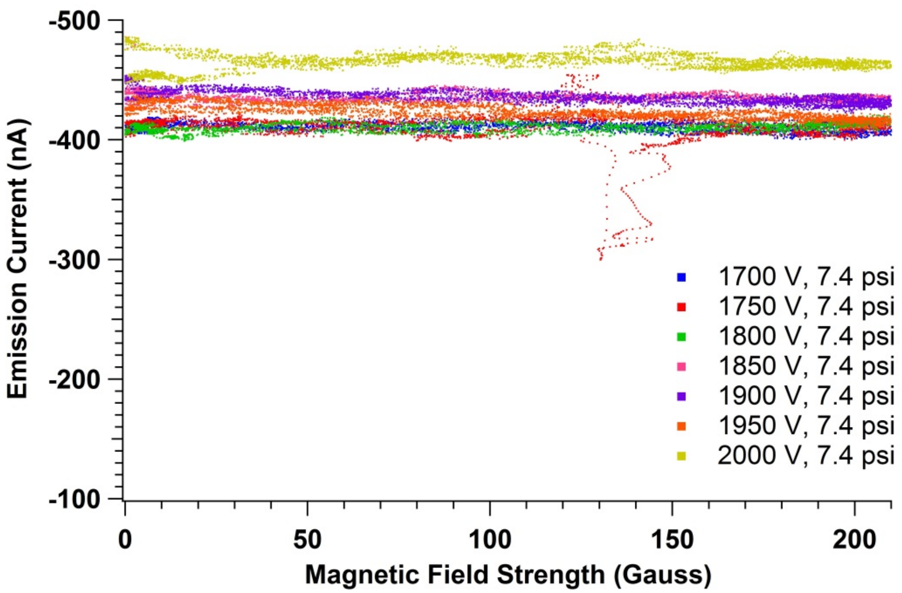
Existing Electrospray Theory (over 400 citations):

Fernandez de la Mora, J., and Loscertales, I.G., "The current emitted by highly conducting Taylor cones," J. Fluid Mech. 260, 155-184, 1994.

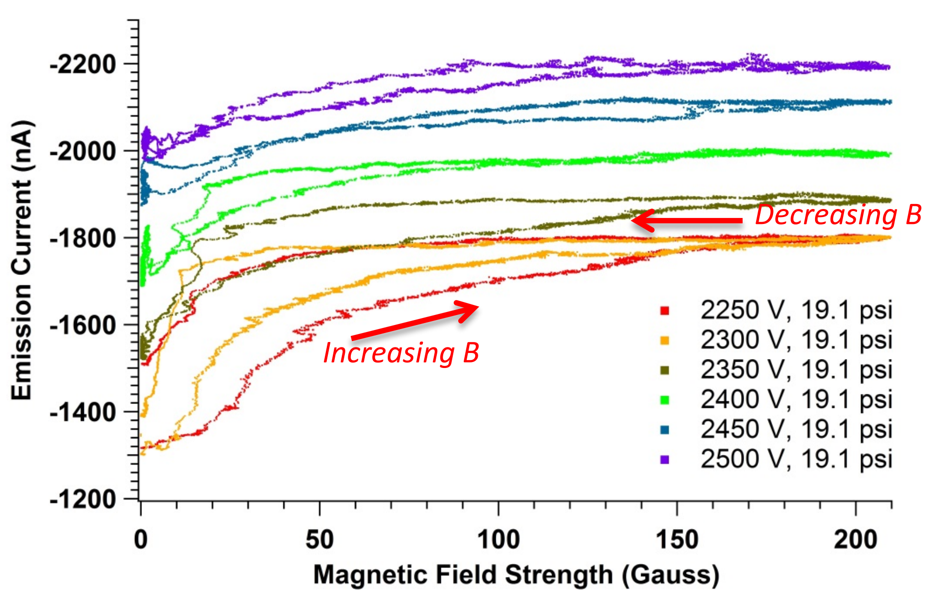
$$I \sim \sqrt{\frac{\gamma Q K}{\varepsilon}}$$

Spray current → I; Surface tension → γ; Flow rate → Q; Conductivity → K; Permittivity → ε

Pure EMIM-NTf2



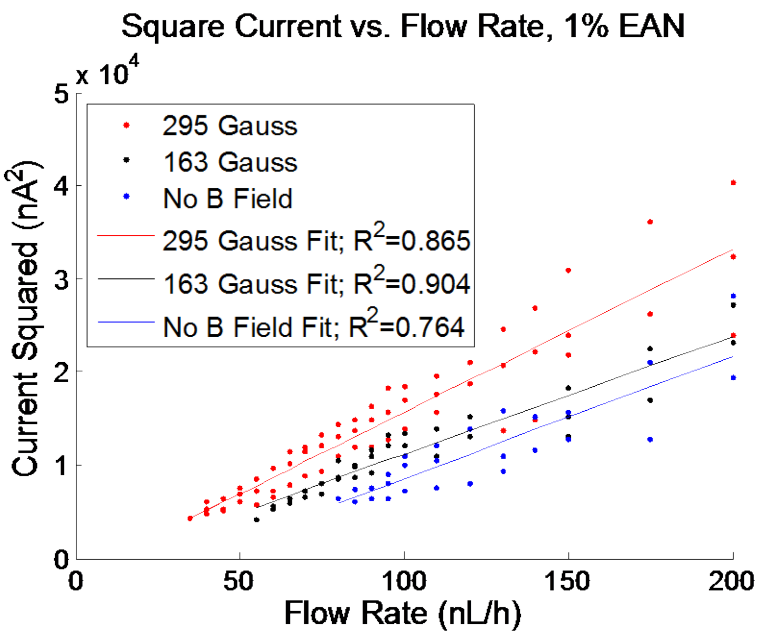
EMIM-NTf2 Ferrofluid

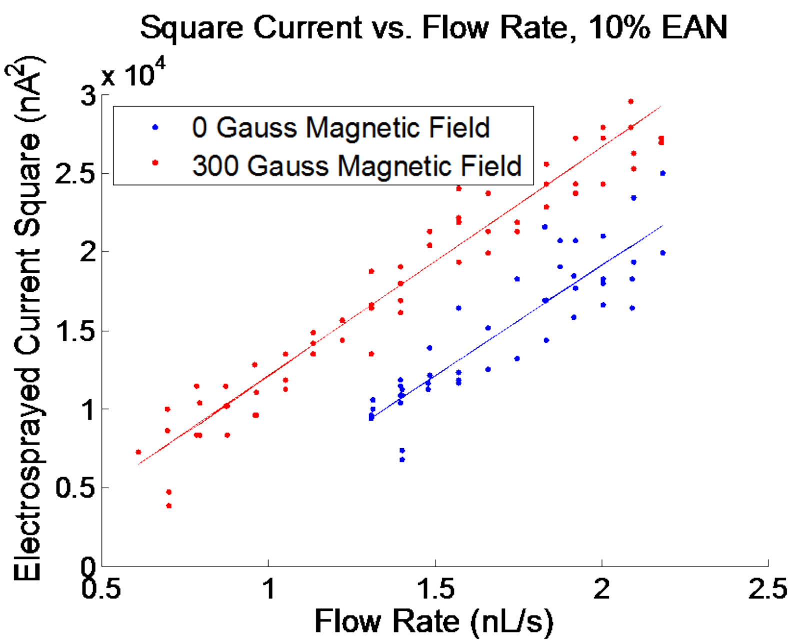


Magnetic effects increase current by ~ 40%

Capillary Spray Results

Existing Electrospray Theory: $$I \sim \sqrt{\frac{\gamma Q K}{\varepsilon}}$$

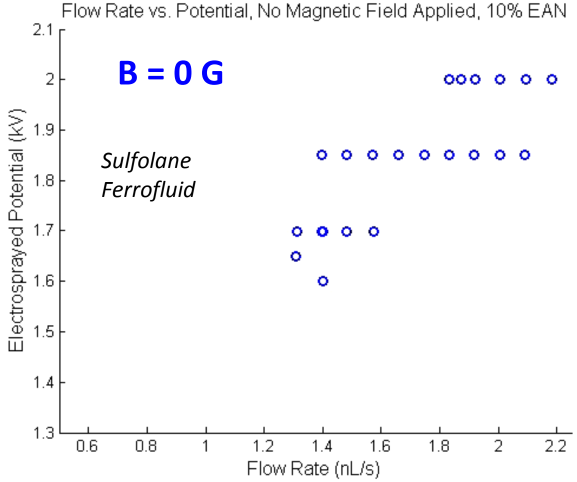




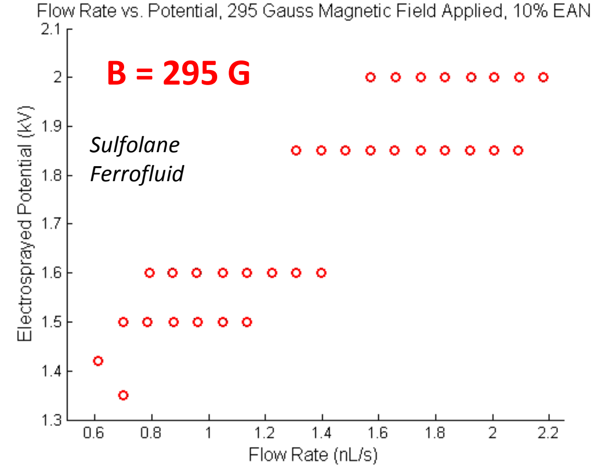
Current still scales with square root of flow rate, but magnetic field increases the magnitude

Magnetic Stress Extends Spray Stability Range

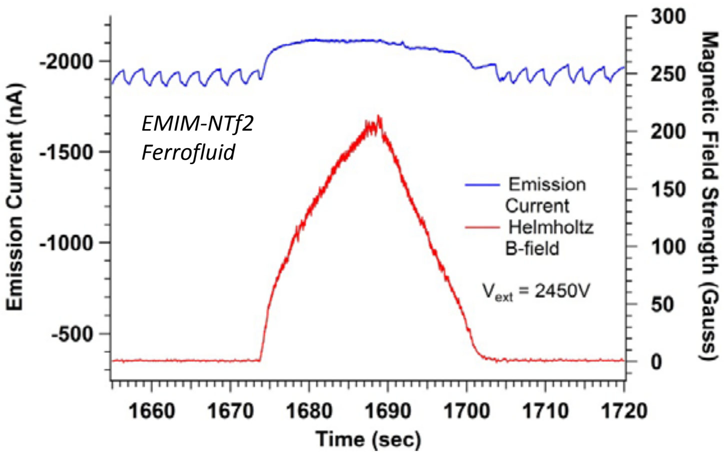
Flow Rate vs. Potential, No Magnetic Field Applied, 10% EAN



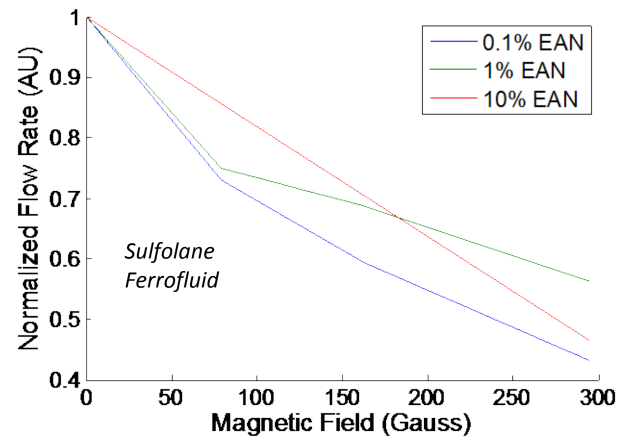
Flow Rate vs. Potential, 295 Gauss Magnetic Field Applied, 10% EAN



Magnetic Field Damps Oscillations



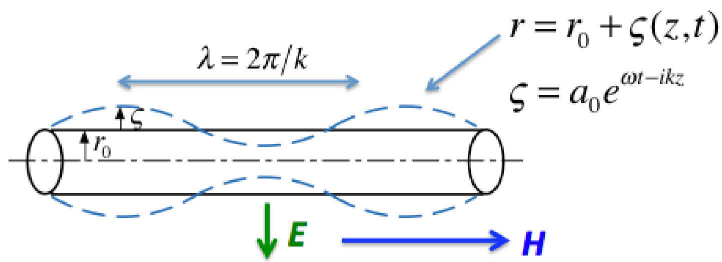
Minimum Normalized Flow Rate vs. Magnetic Field

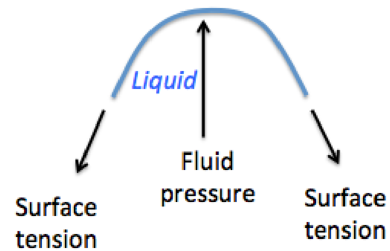


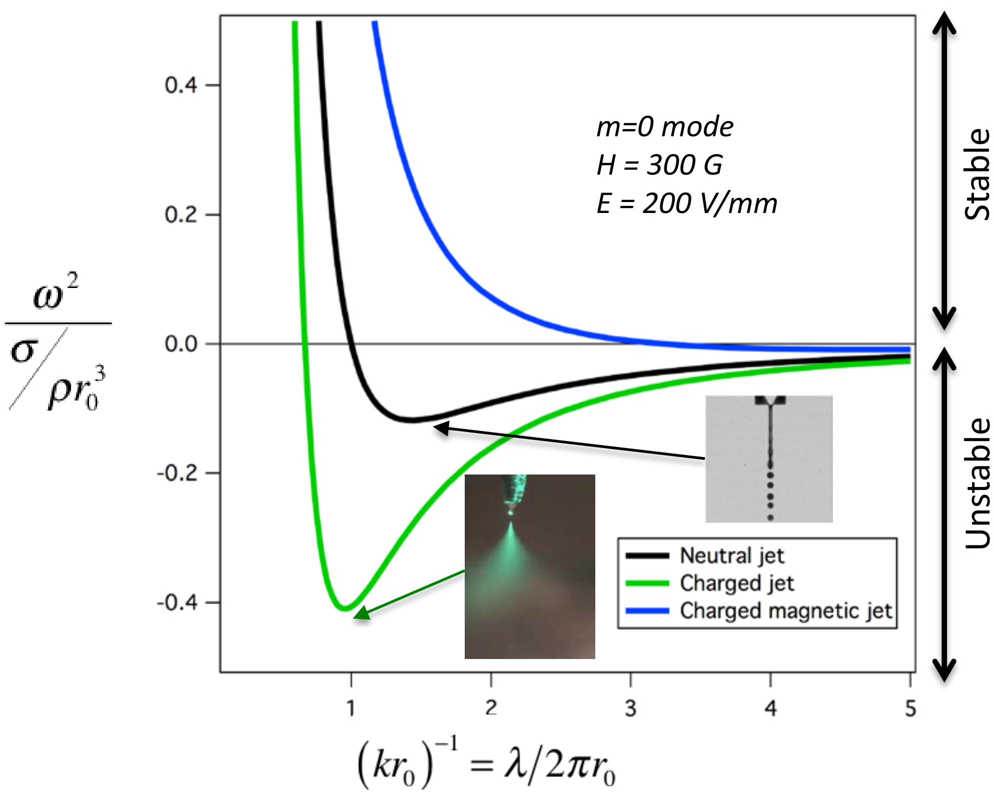
Lower stable flow rates will enable smaller droplet sizes

Theoretical Model of Jet Stability

Dispersion Relation for Surface Waves







Theoretical model of fluid cylinder stability against surface perturbation

Liquid is electrically conducting ferrofluid

Axial magnetic field has a stabilizing effect against surface perturbations

Dipole alignment augments surface tension

$$\Delta U = \frac{1}{2}\rho g \iint z^2(x,y)\,dx\,dy + \sigma \iint \sqrt{1+\left(\nabla z\right)^2}\,dx\,dy - \frac{1}{2}\iiint \mu_0 \left[\frac{\left(\mu_r - 1\right)}{1+N\left(\mu_r - 1\right)}\right] H_0^2\,dx\,dy\,dz$$

Gravitational

Surface Tension

Magnetic

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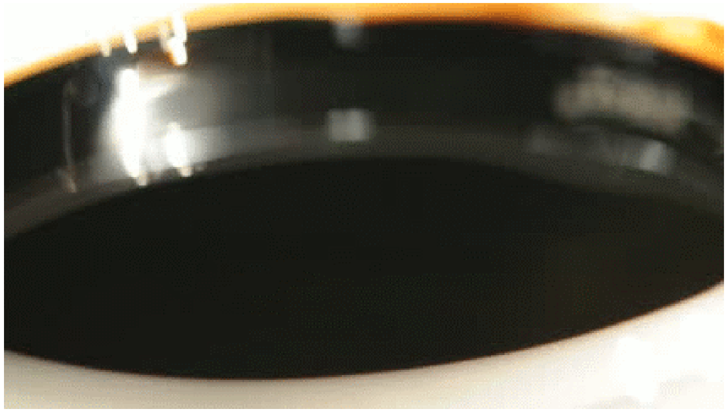
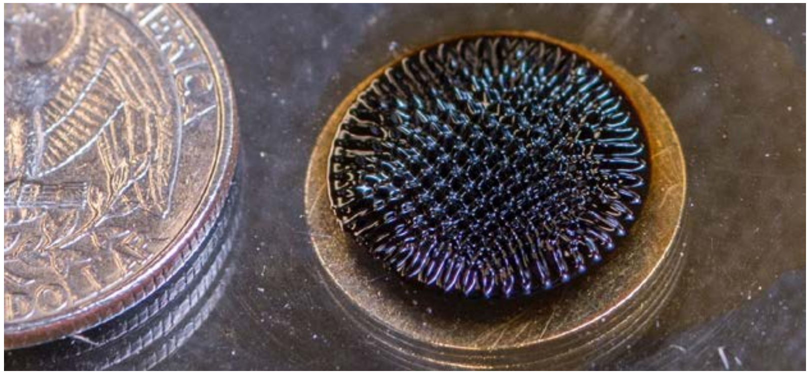
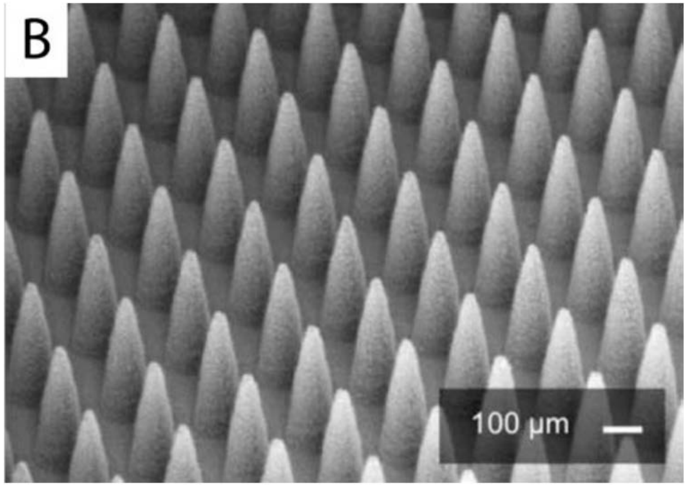
Self-assembling Array of Electrospray Emitters Fabricated from the Propellant Itself

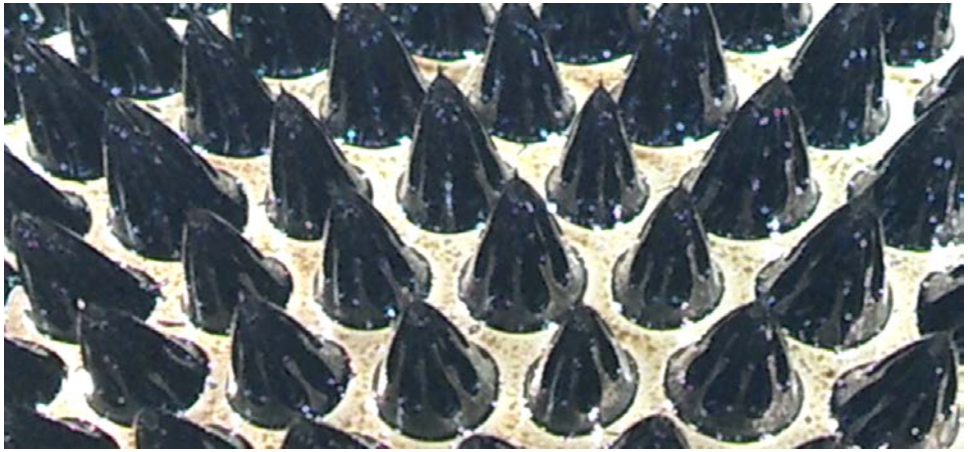




Emitter array fabricated in silicon

Rosensweig instability in ionic liquid ferrofluid





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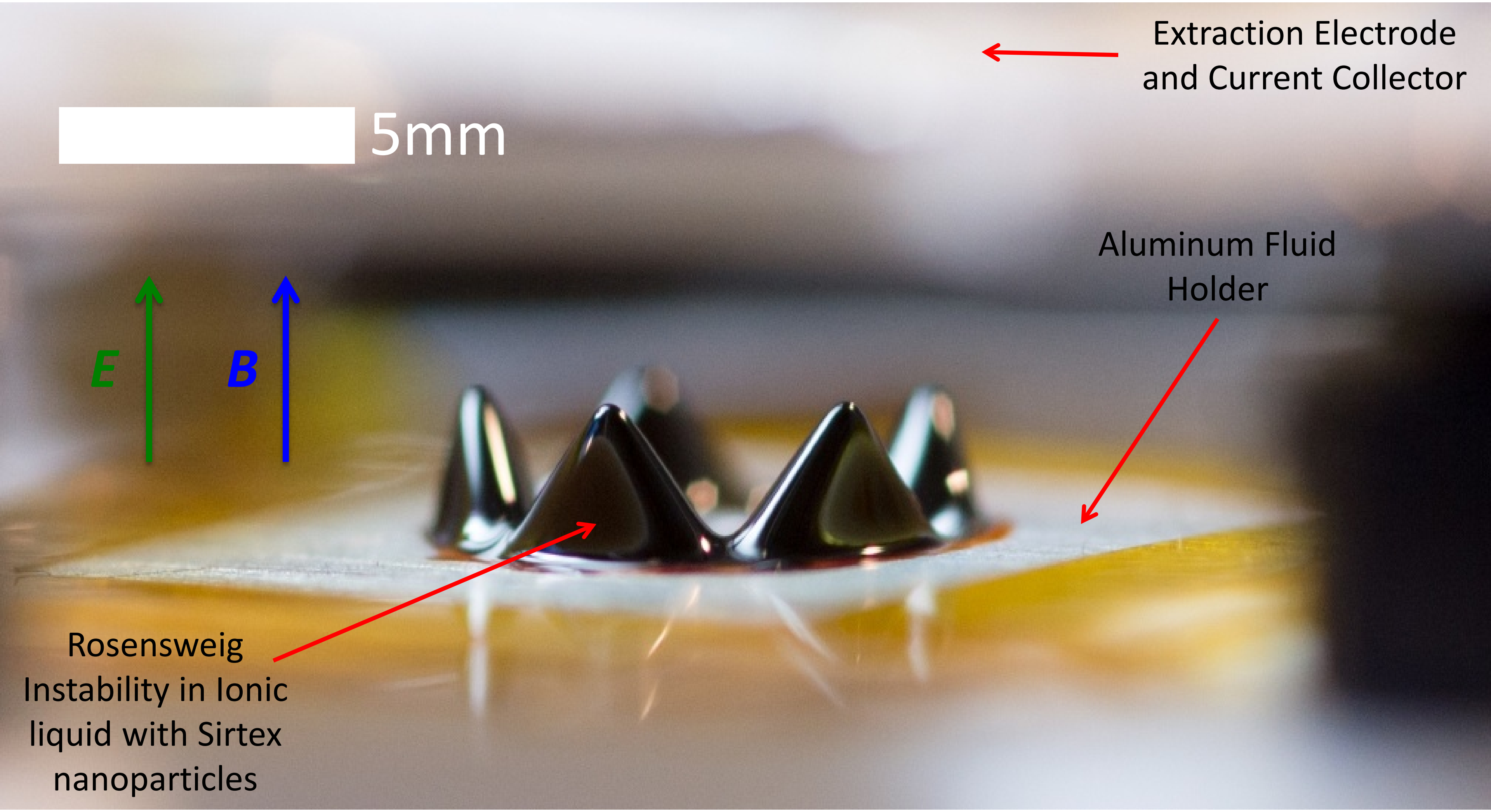
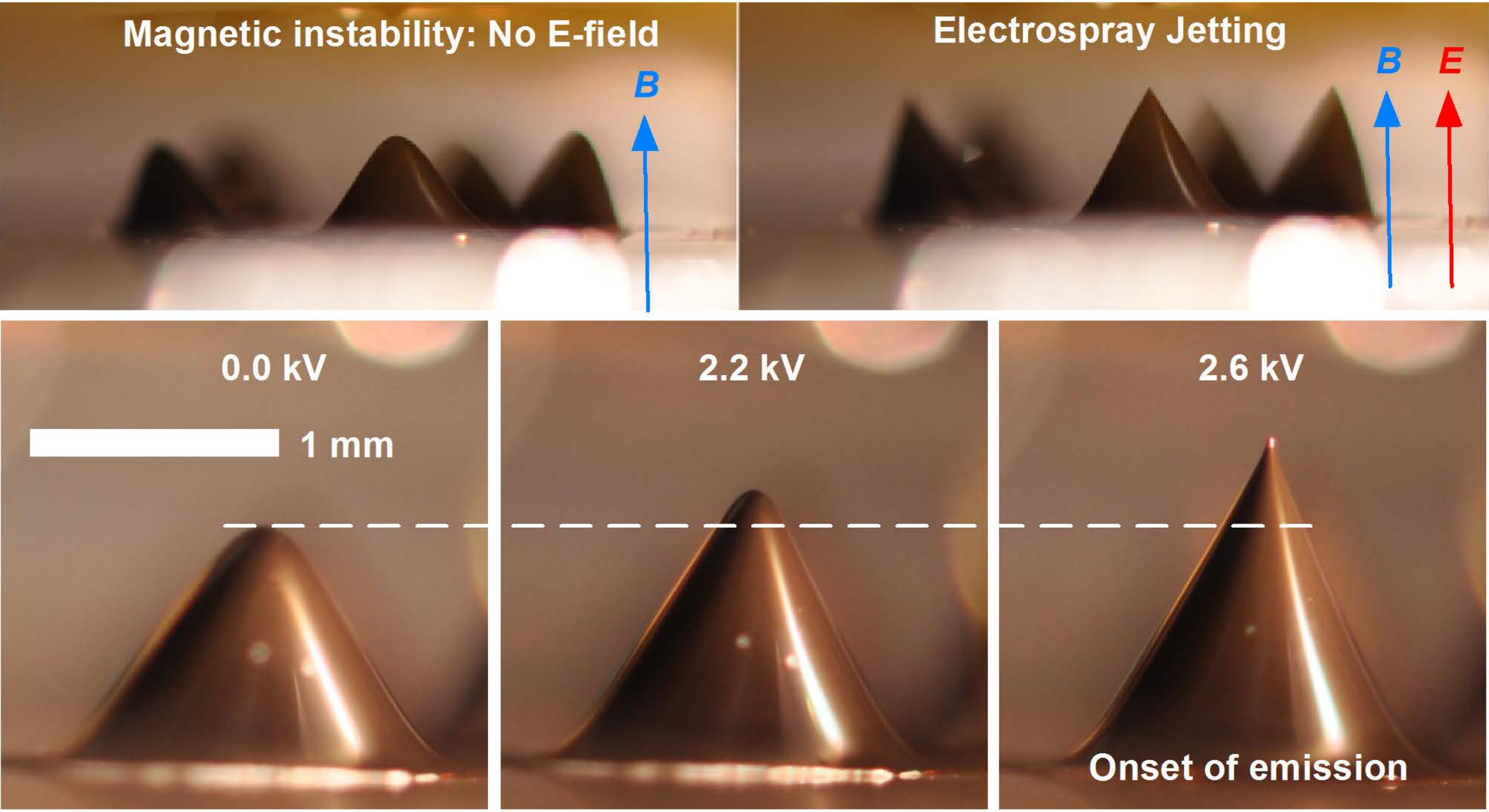
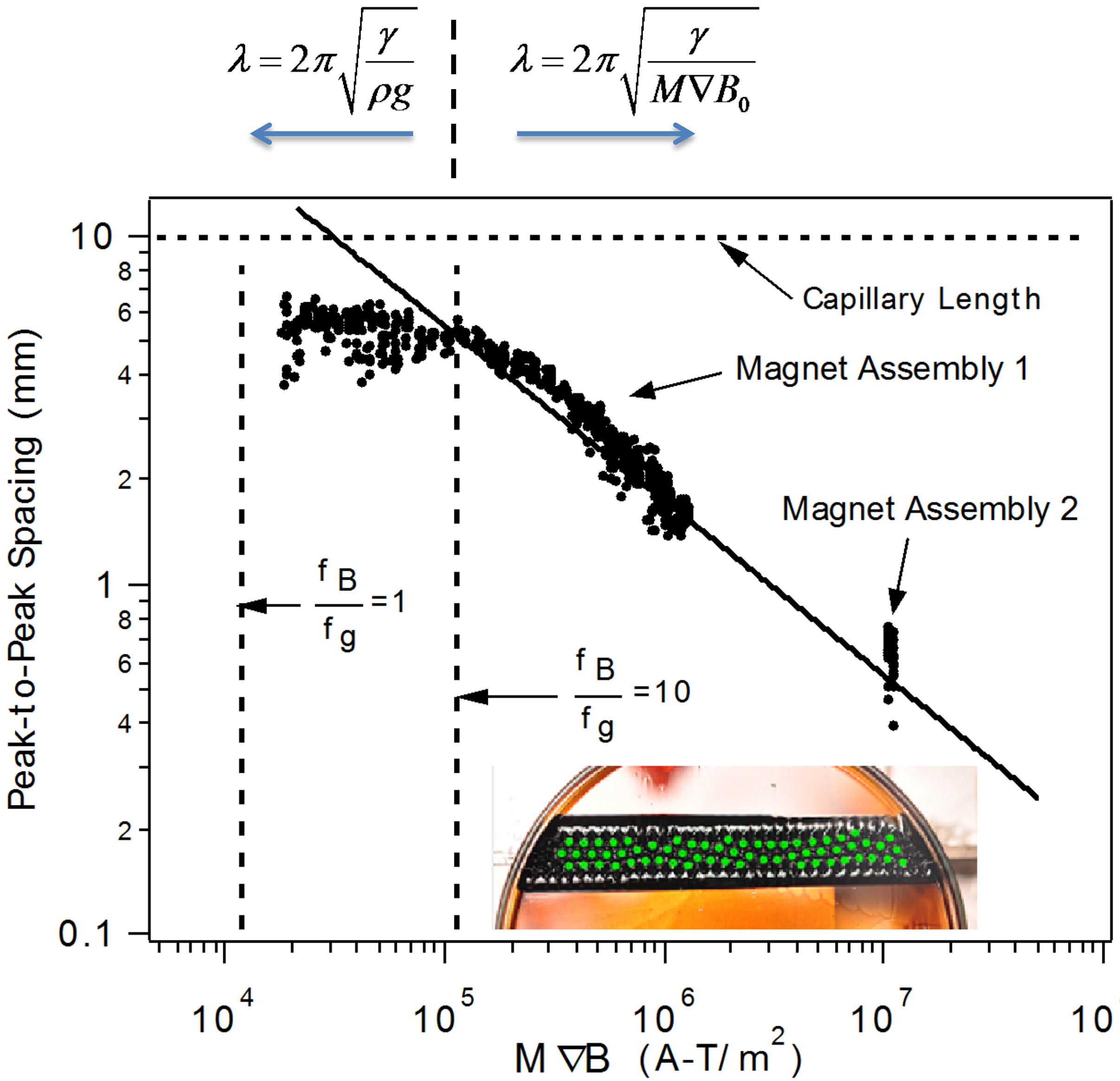
ILLINOIS

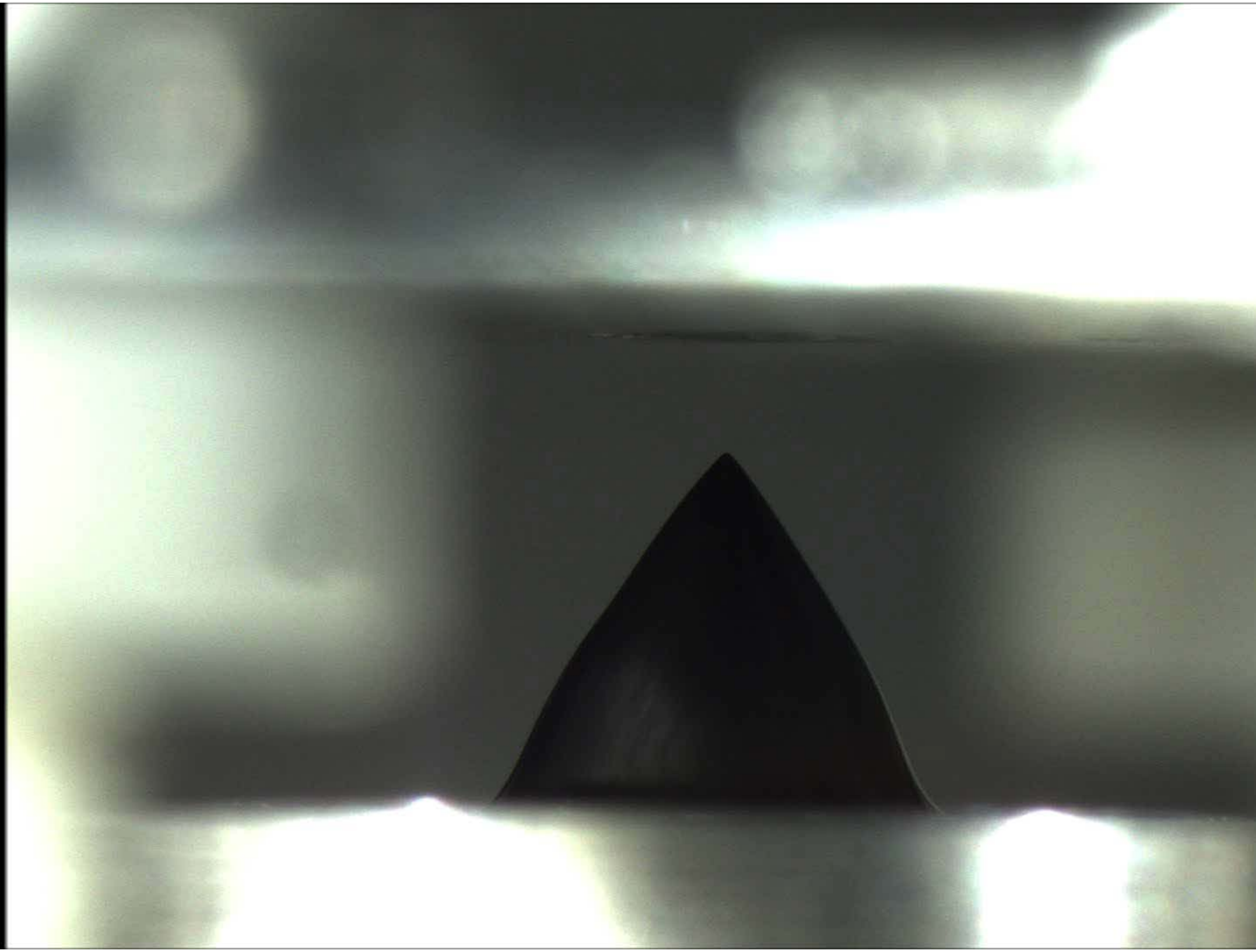



Magnetic instability: No E-field
B
Electrospray Jetting
B
E
0.0 kV
1 mm
2.2 kV
2.6 kV
Onset of emission

Yale

MichiganTech





↑ ***M*** Permanent Magnet ↑ ***M***

Where we're going…