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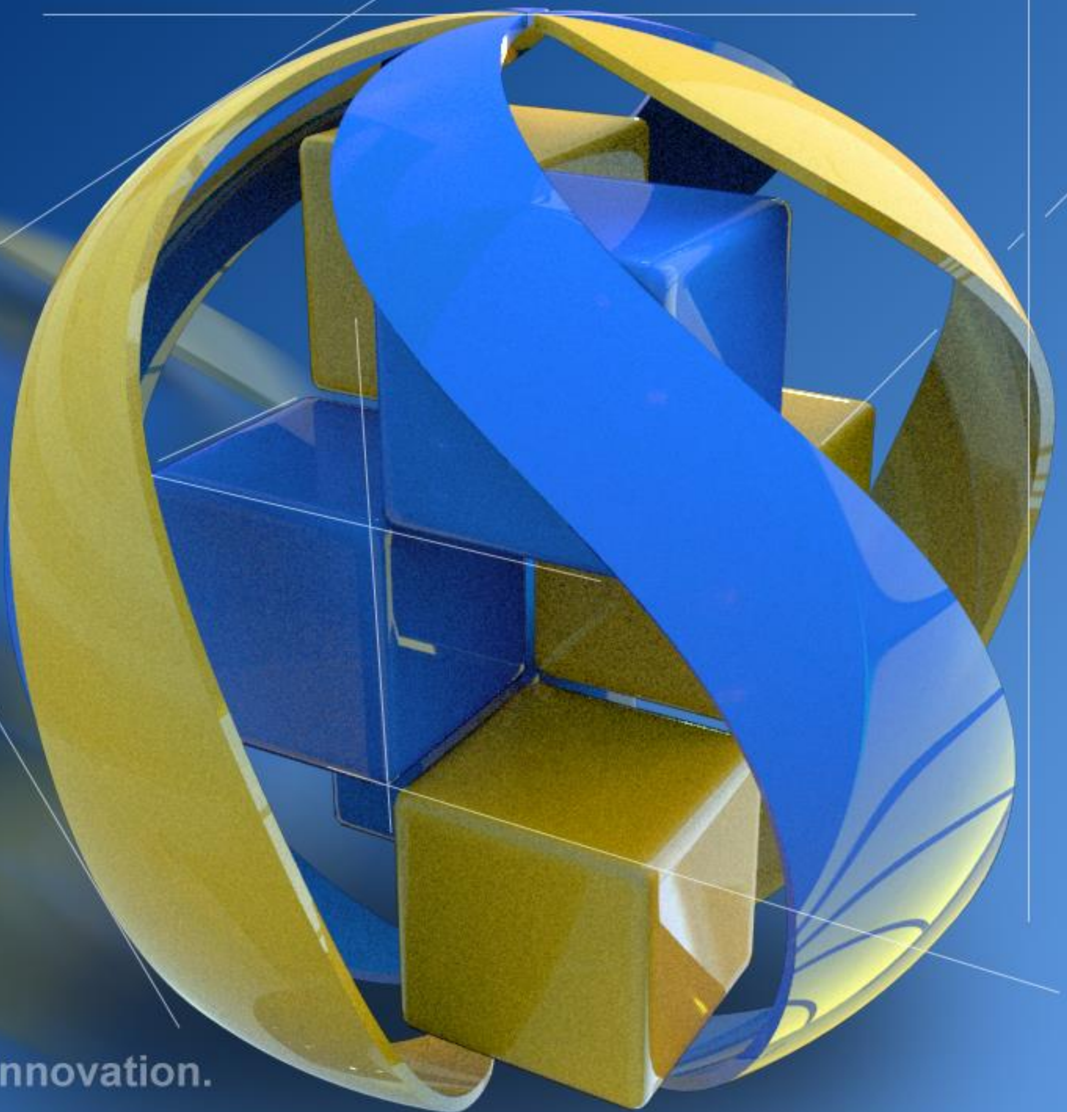

The convergence of research and innovation.

Improved Charge Amplification in the Liquid-Metal Microfluidic Portable Energy Transducer (LiMMPET)

10/3/2019

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COMSOL CONFERENCE
2019 BOSTON

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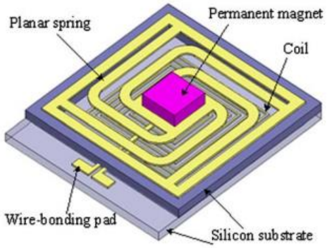
Background: Energy Harvesters

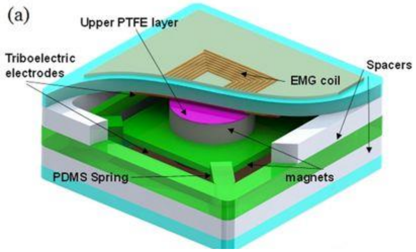


Wang et al., Microsyst Technol (2009) 15:941–951

Electromagnetic

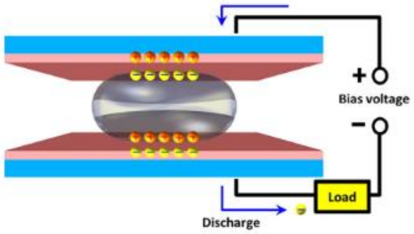
Source: R. Niewiroski, Wikipedia

Source: AF.mil



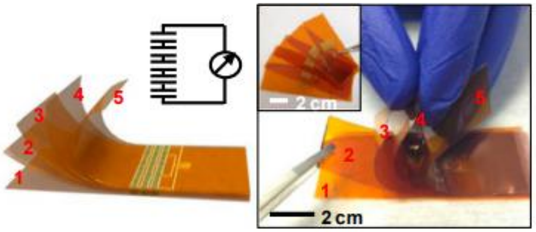
Gupta et al., Broadband Energy Harvester, Scientific Reports (2017)

Hybrid



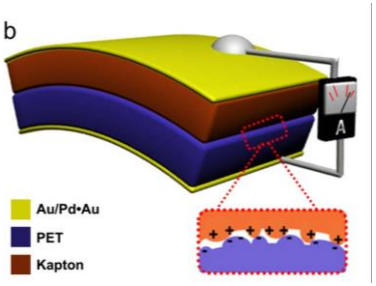
Yang et al., Nano Energy (2016) 31:450-455

Reverse Electrowetting



Dagdeviren et al., Conformal piezoelectric energy harvesting, PNAS (2014)

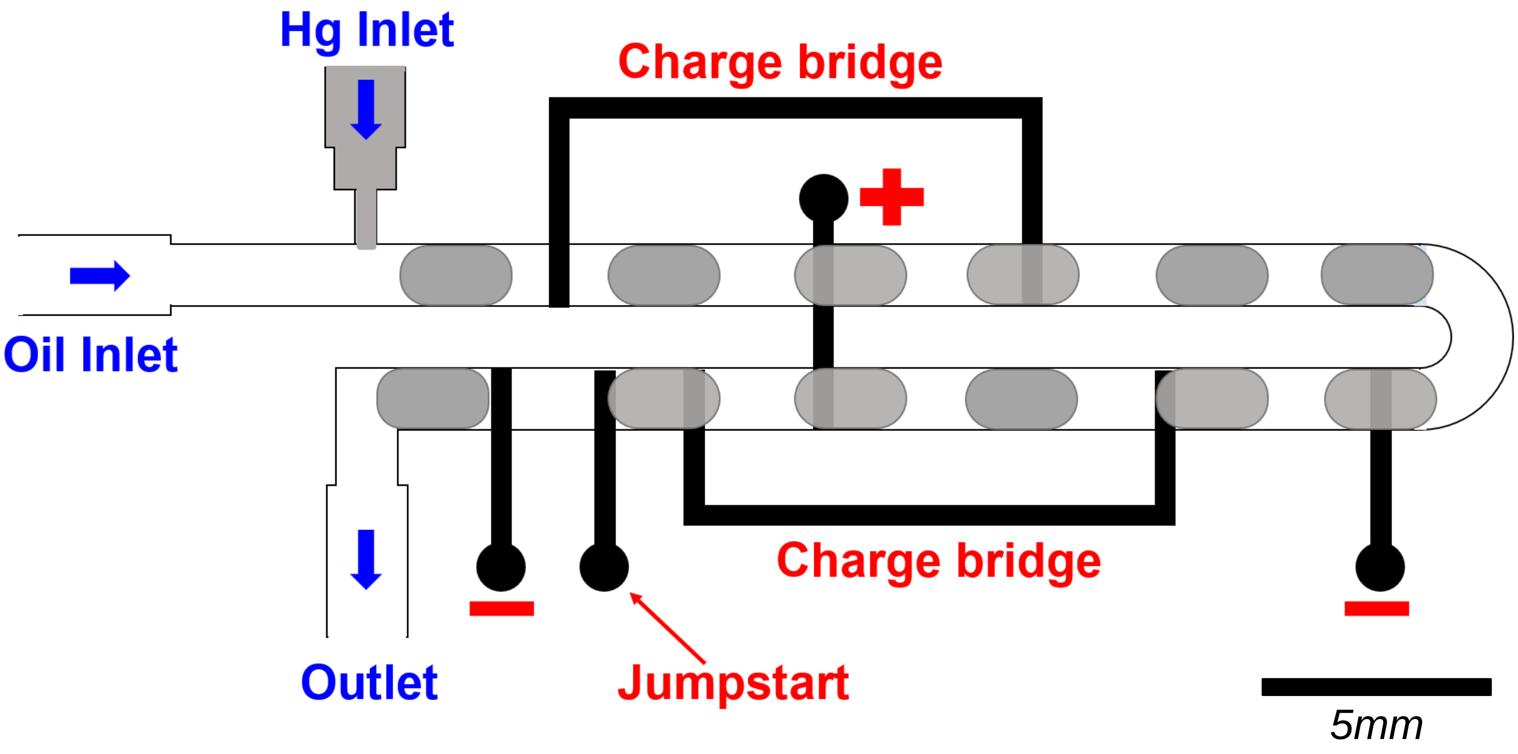
Piezoelectric



F.-R. Fan, et al., Flexible triboelectric generator, Nano Energy (2012)

Triboelectric

Liquid-Metal Microfluidic Portable Energy Transducer (LiMMPET)

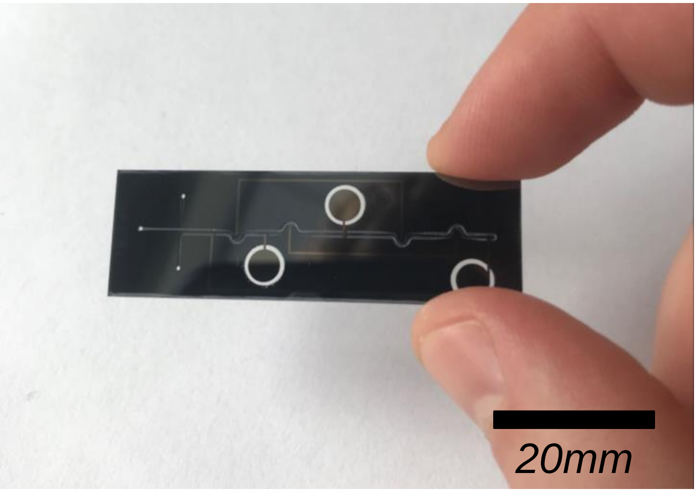


Schematic of the LIMMPET device.

Liquid-Metal Microfluidic Portable Energy Transducer (LiMMPET)

Wimshurst machine.

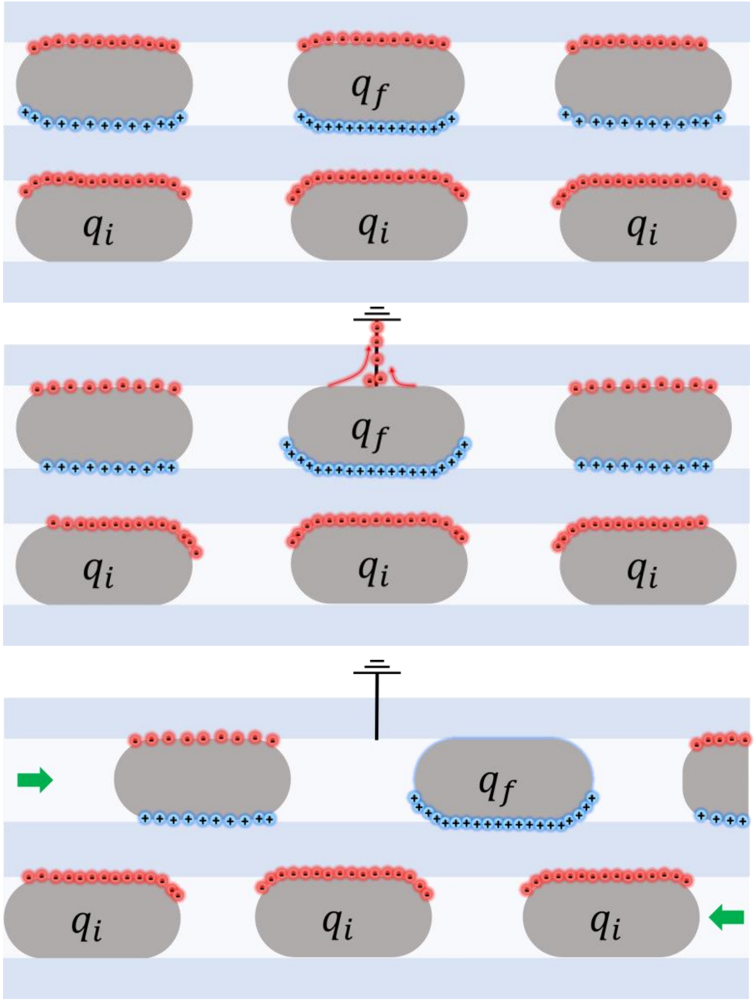
arborsci.com/products/wimshurst-machine



LIMMPET device.

Liquid-Metal Microfluidic Portable Energy Transducer (LiMMPET)

Electrostatic induction causes net charge imbalance

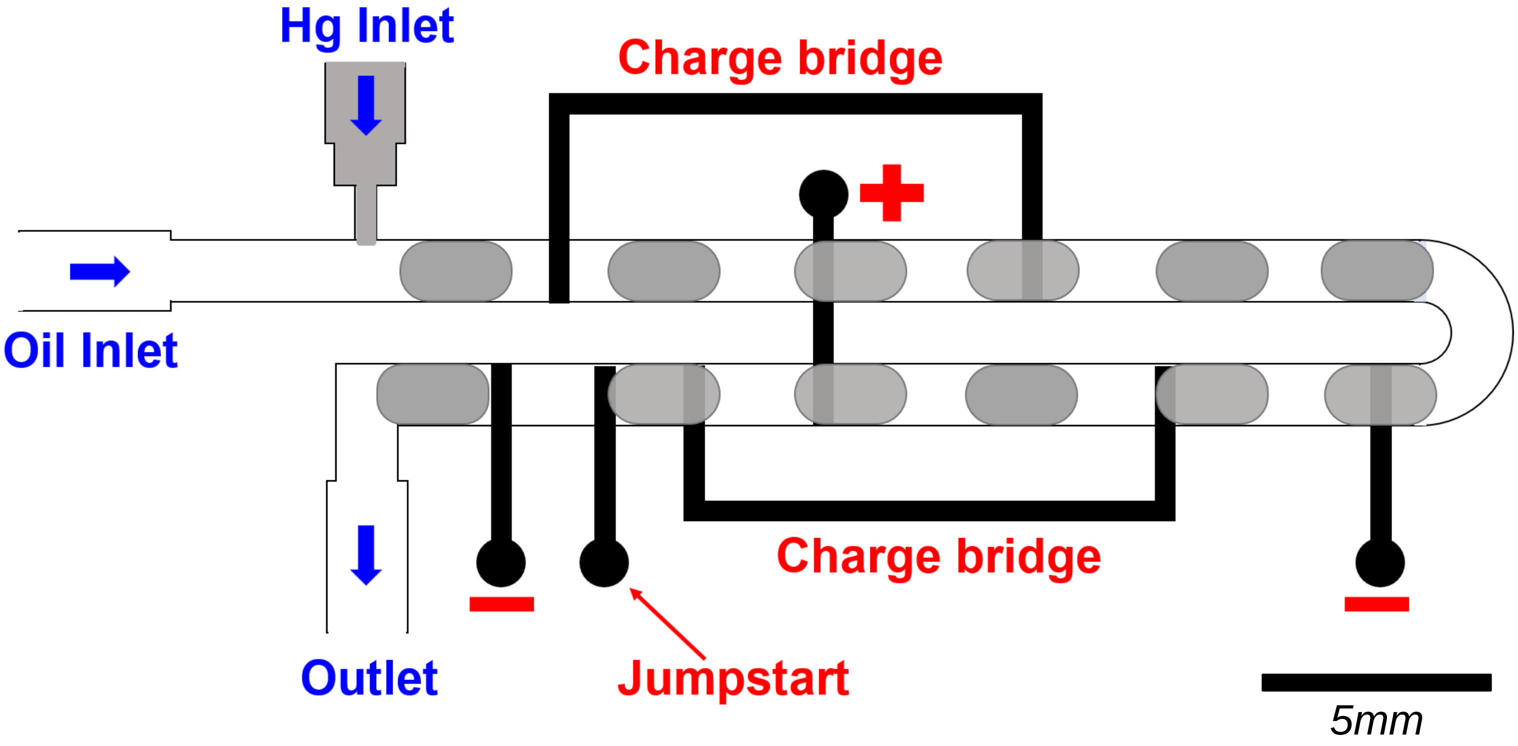


Neutral droplet q_f experiences induced charge separation due to charged droplets q_i in lower channel.

Charge is transported out of q_f if connected to a conductor

Droplet q_f maintains net charge imbalance after pulling away from conductor

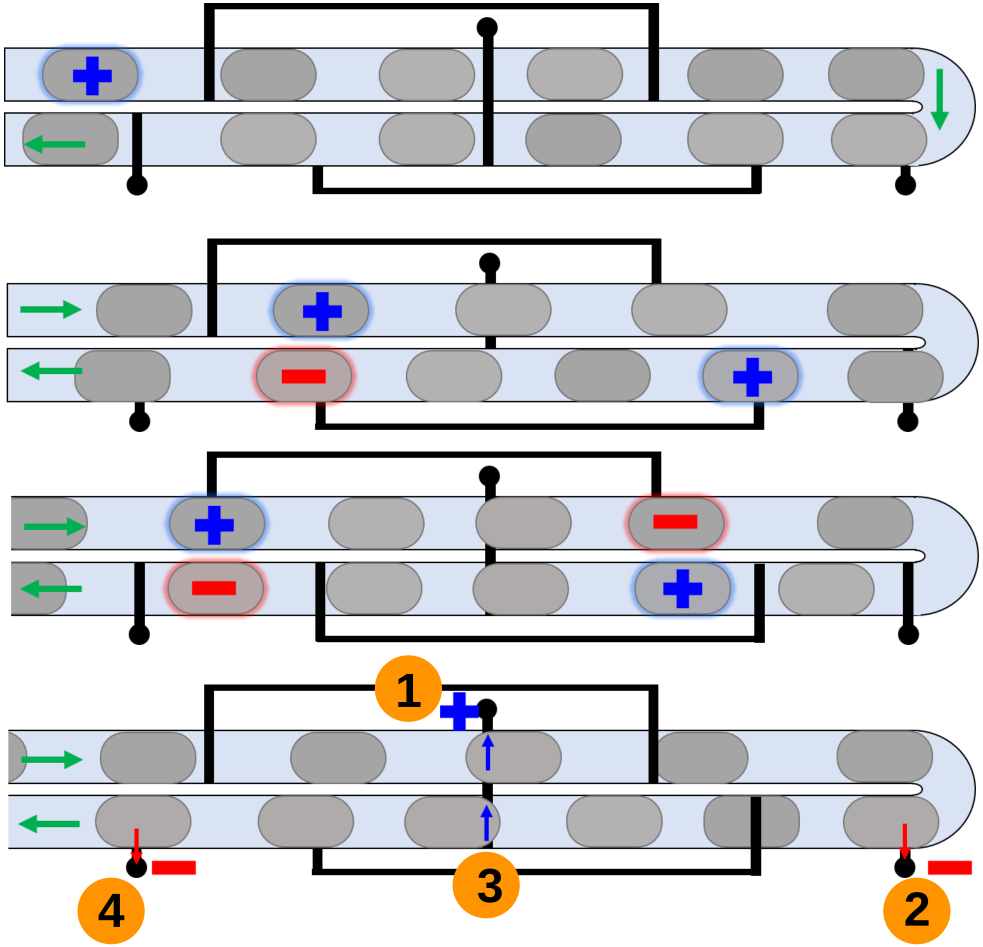
Liquid-Metal Microfluidic Portable Energy Transducer (LiMMPET)



Schematic of the LIMMPET device.

Operation

4-Step Energy Harvesting Process



Charge seeded.

Induced charge separation.

Charge separation.

Charge collection.

Theory

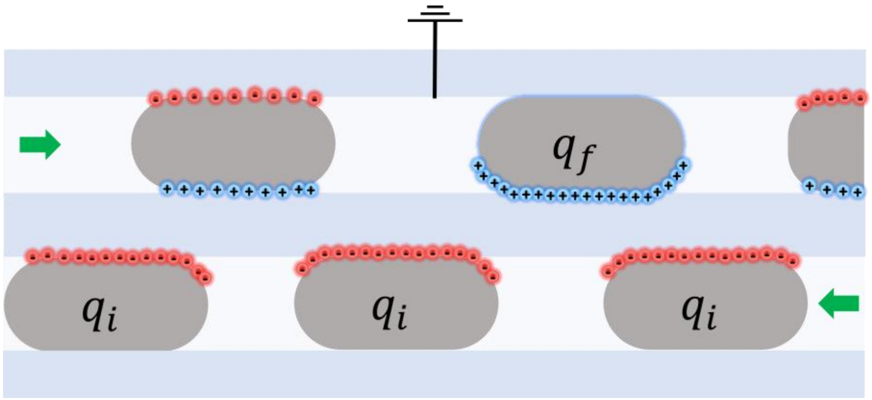
Device Performance	
Breakdown-limited max power output	$P_{max} = \frac{q_{max}}{C_{droplet}} 2\pi\sigma_{max} v w = \varepsilon_0 \varepsilon_r E_{max}^2 \pi w^2 v$
Power dissipated due to viscous drag	$P_{dissipated} = \Delta P = 32\eta L v^2$
Efficiency	$\alpha = \frac{P_{max}}{P_{max} + P_{dissipated}} = \frac{\varepsilon_0 \varepsilon_r E_{max}^2 \pi w^2 v}{\varepsilon_0 \varepsilon_r E_{max}^2 \pi w^2 v + 32\eta L v^2}$
Efficiency	$\boldsymbol{\alpha > 95\%}$

Theory

Charge Amplification Factor

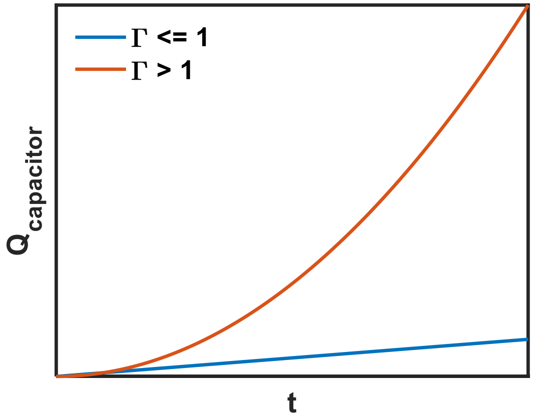
$$\Gamma = {}^{q_f}/_{q_i}$$

Where q_f is the induced charge on a droplet and q_i is the charge on an inducing droplet.



Effect of Γ on Power Generation

Charge Accumulation Rate



Analytical Calculation

$$Q = C \cdot V$$

Maxwell Capacitance Matrix

$$C = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1N} \\ C_{21} & C_{22} & \cdots & C_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ C_{N1} & C_{N2} & \cdots & C_{NN} \end{bmatrix}$$

2D COMSOL Multiphysics ® Model: Overview

Electric Currents Equations

Charge Conservation $\nabla \cdot \boldsymbol{J} = Q_{j,v}$

Ohm's Law $\boldsymbol{J} = \sigma \boldsymbol{E} + \frac{\partial D}{\partial t}$

Electric Potential $\boldsymbol{E} = -\nabla V$

Laminar Two-Phase Flow Equations

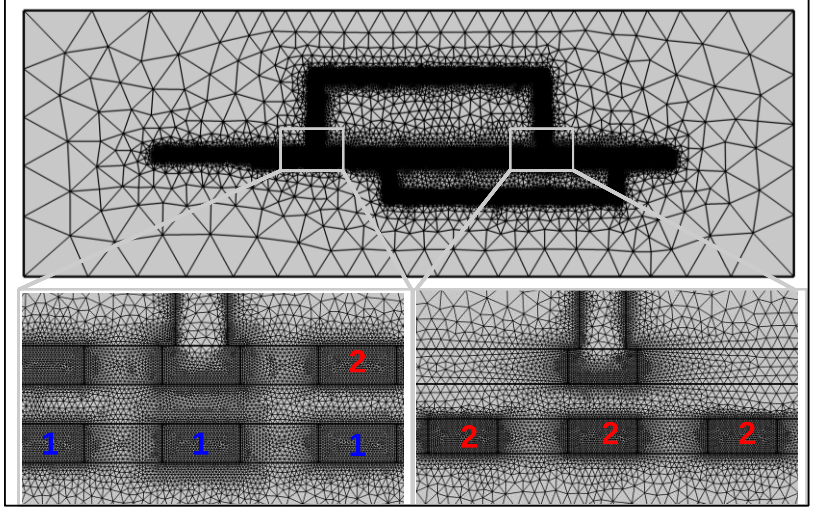
Navier-Stokes $\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = [-p\boldsymbol{I} + \mu(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T)] + \boldsymbol{F}_{st}$

decomposed Cahn-Hilliard Equation

$$\begin{cases} \frac{\partial \phi}{\partial t} + \boldsymbol{u} \cdot \nabla \phi = \nabla \cdot \frac{\gamma \lambda}{\varepsilon^2} \nabla \psi \\ \psi = -\nabla \cdot \varepsilon \nabla \phi + (\phi^2 - 1) + \frac{\varepsilon^2}{\lambda} \partial \mathrm{f} / \partial \phi \end{cases}$$

Mobility parameter $\gamma = \chi \varepsilon^2$

Material	Oil	Mercury
Density	1.766 g/cm^3	13.55 g/cm^3
Relative Permittivity	2.09	1
Conductivity	10^{-11} S/m	104384 S/m



Boundary Conditions

Electric Currents: $V = 0$

Phase Field: Outlet

Current Sources

1 $Q_{j,v} = -Q0 * f(t)$

2 $Q_{j,v} = Q0 * f(t)$

Initial Conditions

Electric Currents: $V = 0$

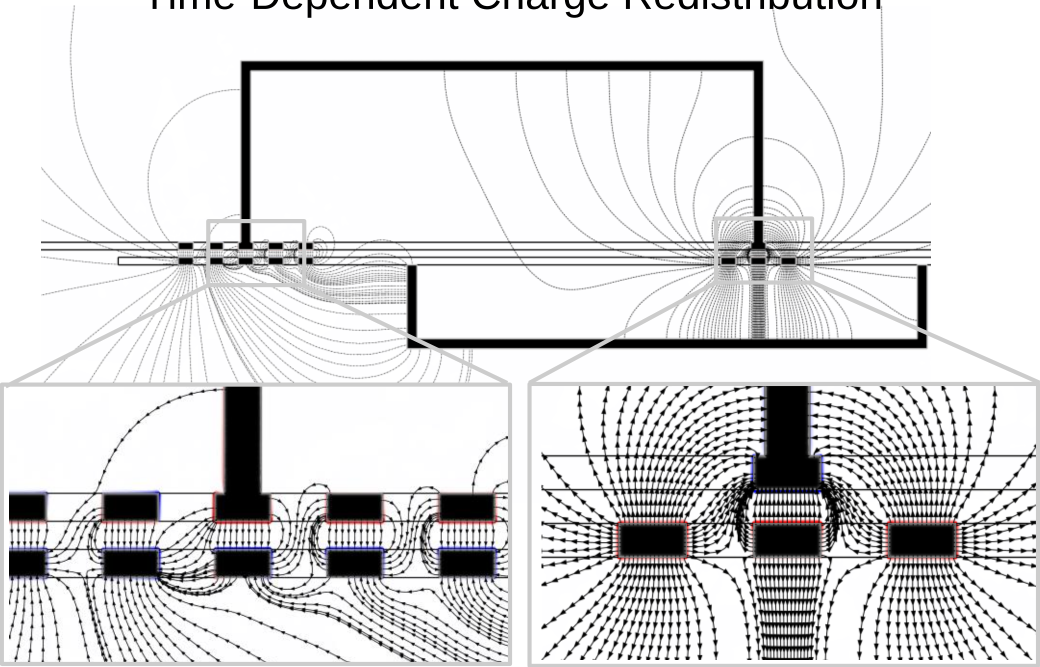
Phase Field (droplets): $\phi = -1$

Phase Field (else): $\phi = 1$

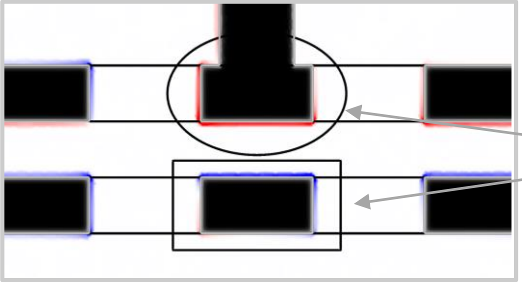
Approximately 181,000 mesh elements in model.

2D COMSOL Multiphysics ® Model: Results

Time-Dependent Charge Redistribution

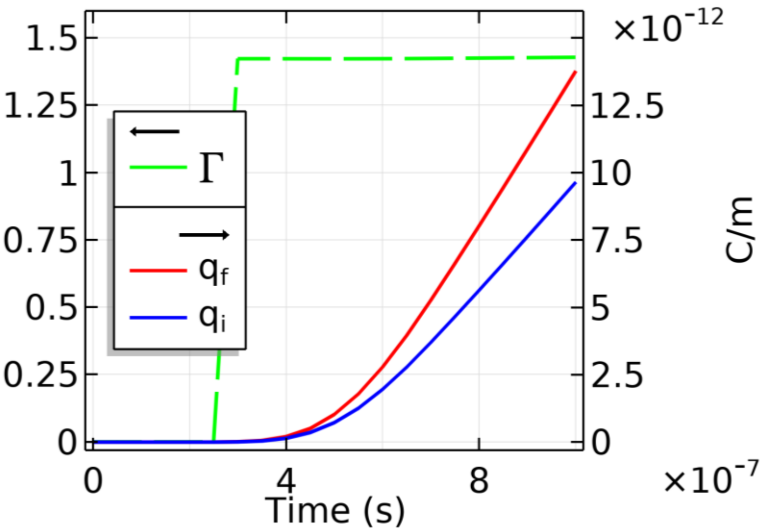


Field lines and space charge density for positively (red) and negatively (blue) charged droplets.



Integration domains for q_f and q_i.

Charge Amplification Factor



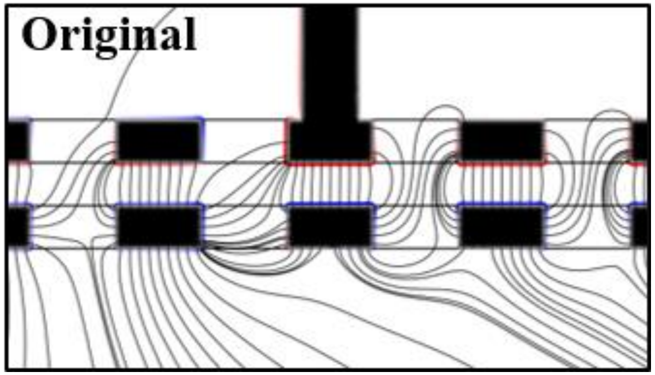
Time dependent charge amplification factor.

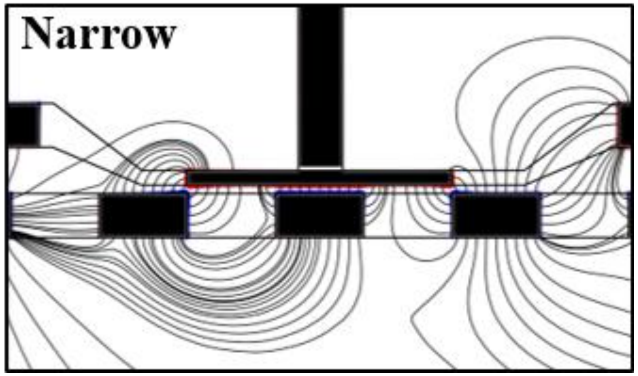
$$\Gamma = {}^{q_f}\!/_{q_i} = 1.43$$

2D COMSOL Multiphysics ® Model: Results

Design Process

1. Channel width ratio





1.43

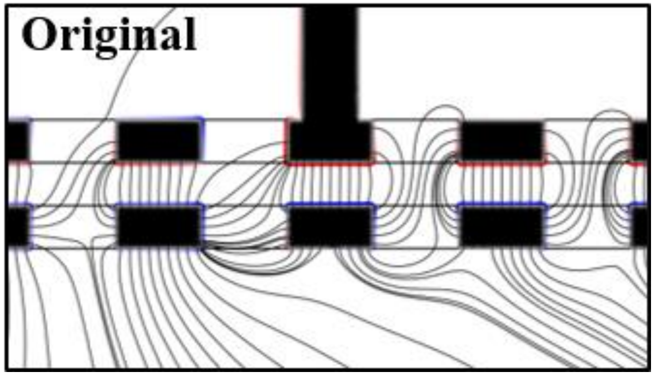
$$\Gamma = {}^{q_f}\!/_{q_i}$$

2.01

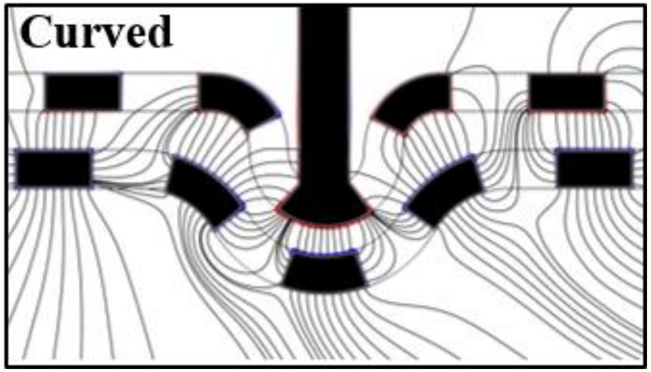
2D COMSOL Multiphysics ® Model: Results

Design Process

1. Channel width ratio
2. Curvature



1.43



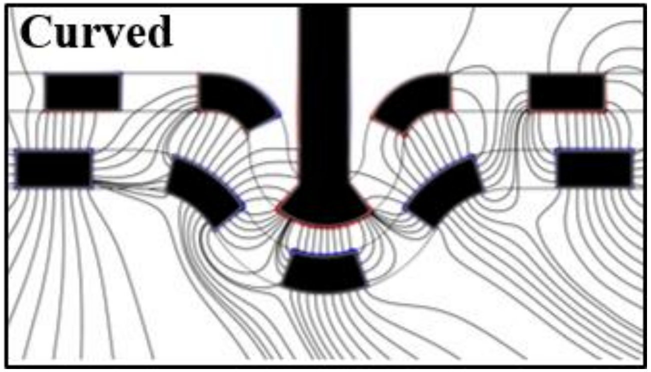
1.80

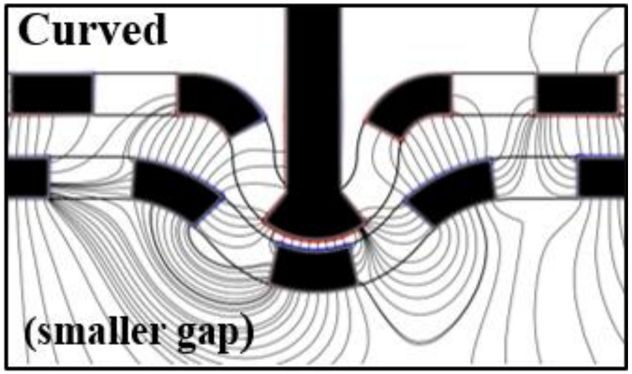
$$\Gamma = {}^{q_f}/_{q_i}$$

2D COMSOL Multiphysics ® Model: Results

Design Process

1. Channel width ratio
2. Curvature
3. Channel gap distance





1.80

$$\Gamma = {}^{q_f}/_{q_i}$$

1.80

2D COMSOL Multiphysics ® Model: Results

Design Process

1. Channel width ratio
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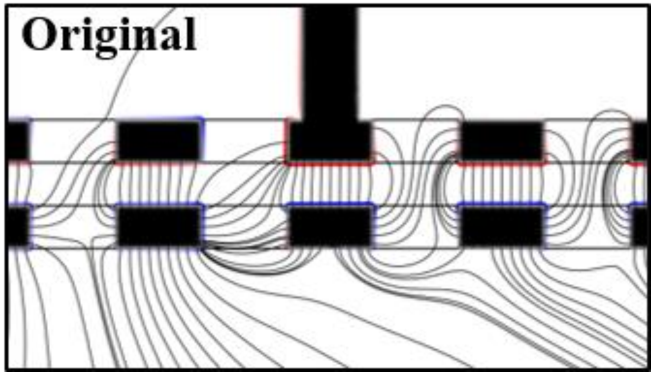
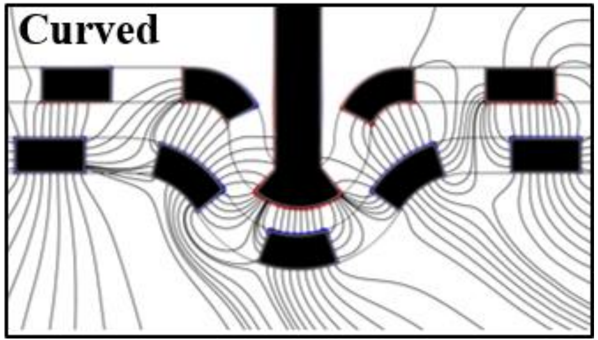
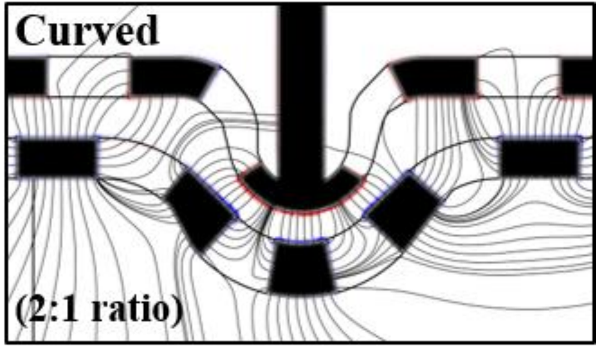


1.43

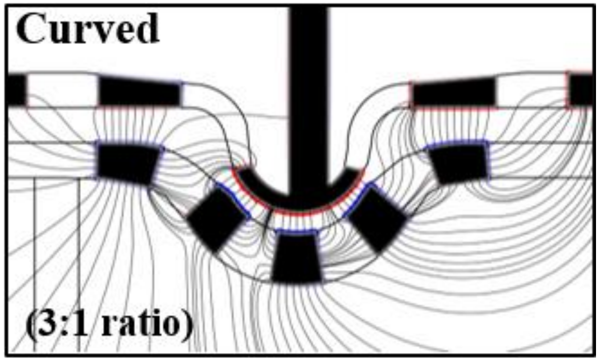
1.80



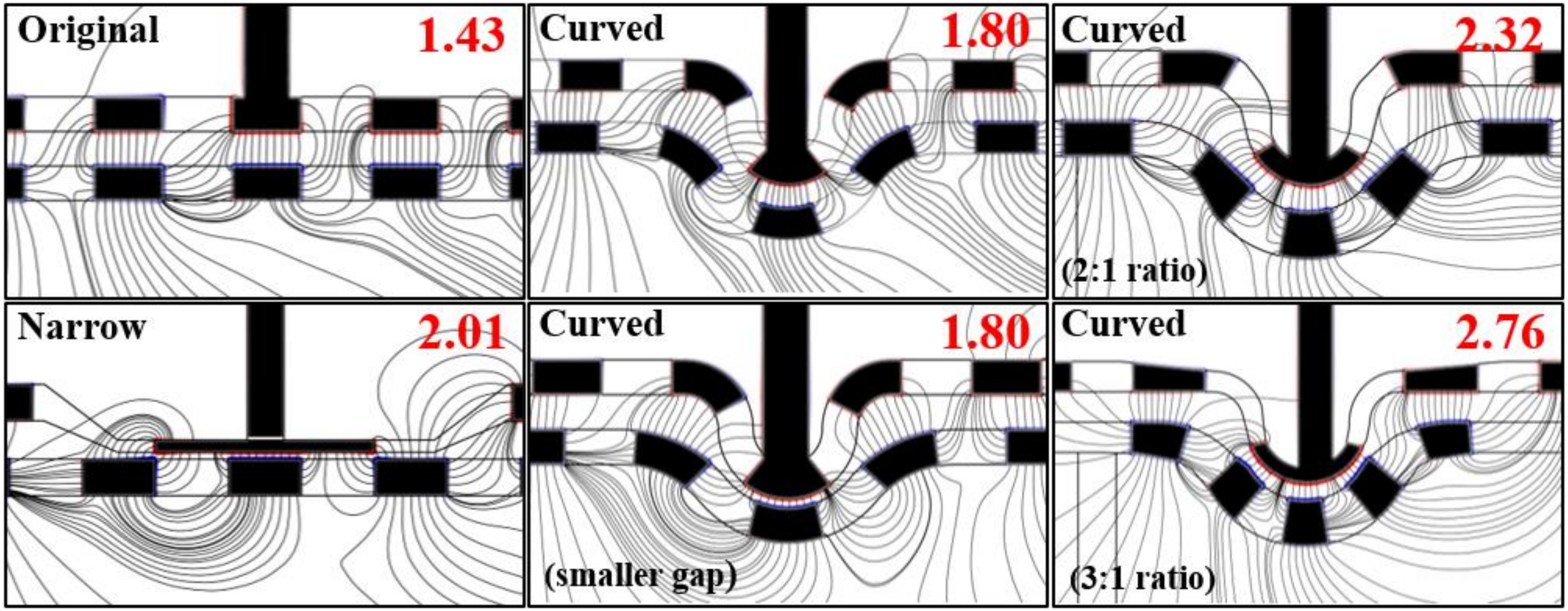
2.32



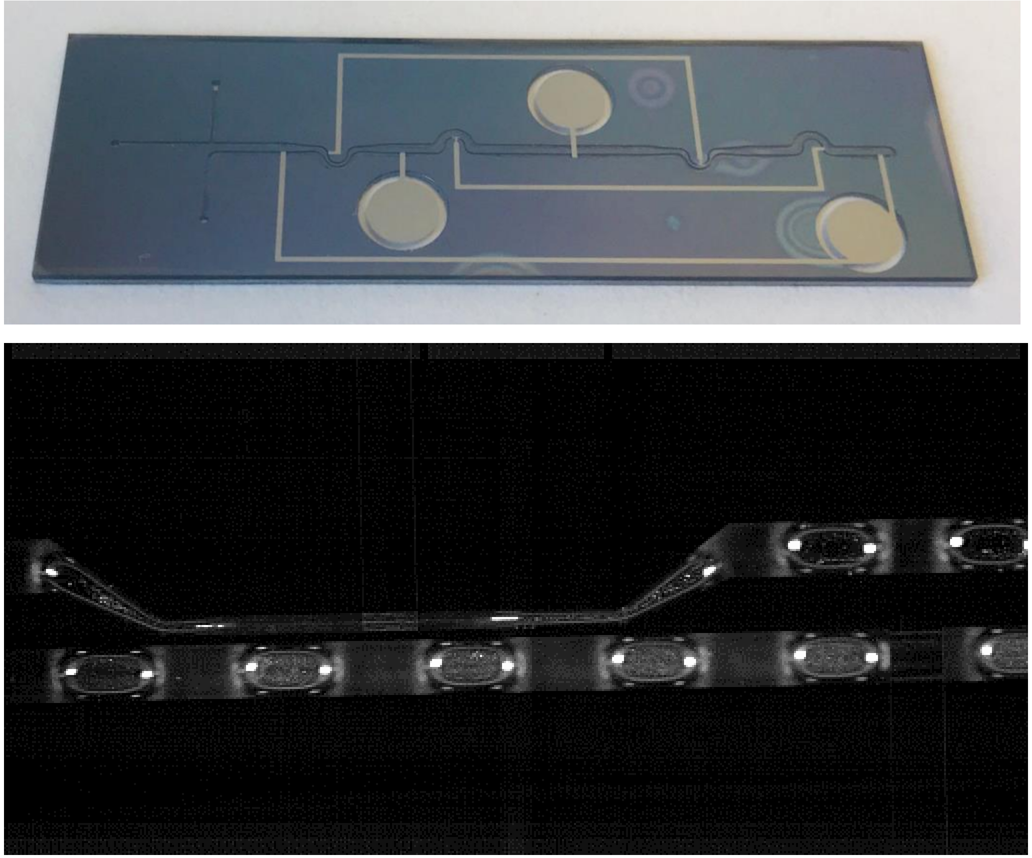
2.76



Results – Charge Amplification Factor



Fabrication and Testing

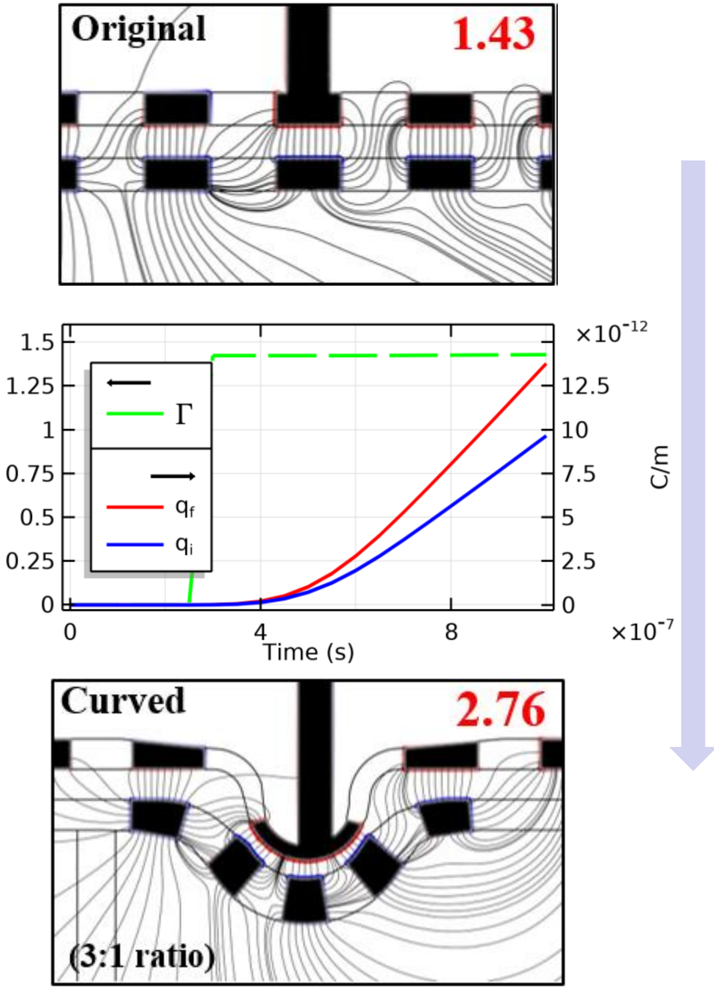


Summary

- COMSOL Multiphysics® was used to improve charge amplification factor in the LIMMPET.
- Numerical analysis demonstrated the importance of key geometric parameters such as channel width ratio and curvature.

Future Directions

- Match experimental charge accumulation with predicted charge amplification factor.
- Model the full dynamic process, including droplet generation and flow dynamics, in COMSOL Multiphysics®.



Thank you!

Questions?