Scalable Flat-Panel Nanoparticle Propulsion Technology for Space Exploration in the 21st Century

NIAC Phase 1

End-of-Project Presentation

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Presentation Outline

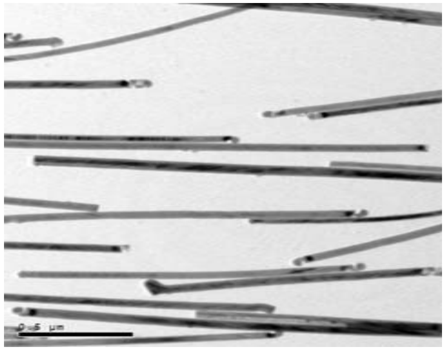
- What is nanoparticle EP (nanoFET)?
- How does nanoFET work?
- What are the advantages offered by nanoparticle EP?
- What have we learned to-date in Phase 1?
- Looking to the future

What is **nanoFET**?

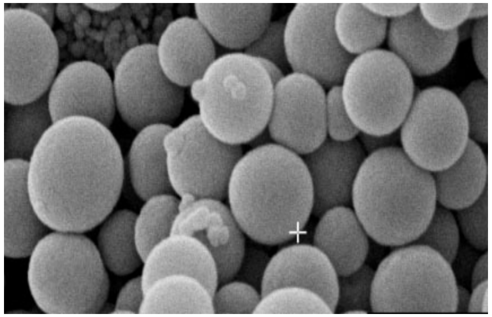
<u>nano</u>particle <u>F</u>ield <u>E</u>mission <u>T</u>hruster

- Electrostatically <u>*charges*</u> and <u>*accelerates*</u> *nanoparticles* as propellant
  - Tremendous flexibility controlling charge/mass *(q/m)* ratio to tune propulsion performance

*Use <u>**nanoparticles**</u> of various geometries and material as <u>**propellant**</u>*



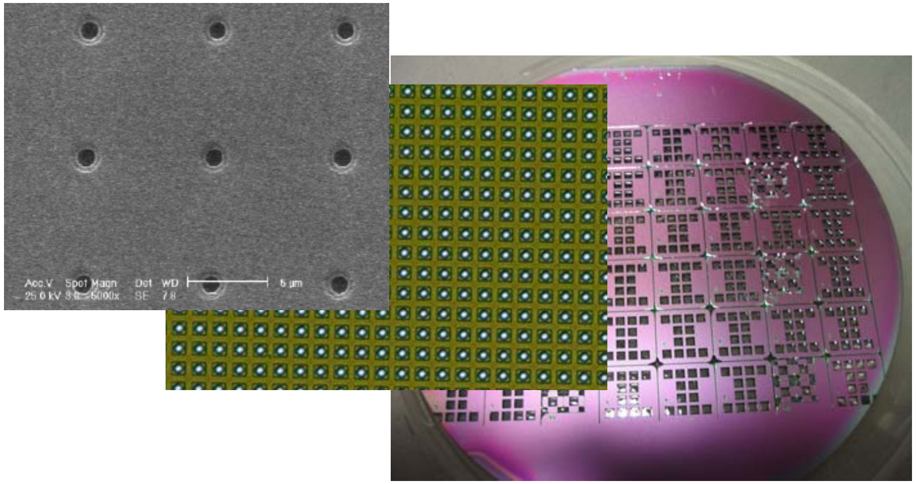
45 nm dia. x 500 nm long



100 nm dia.

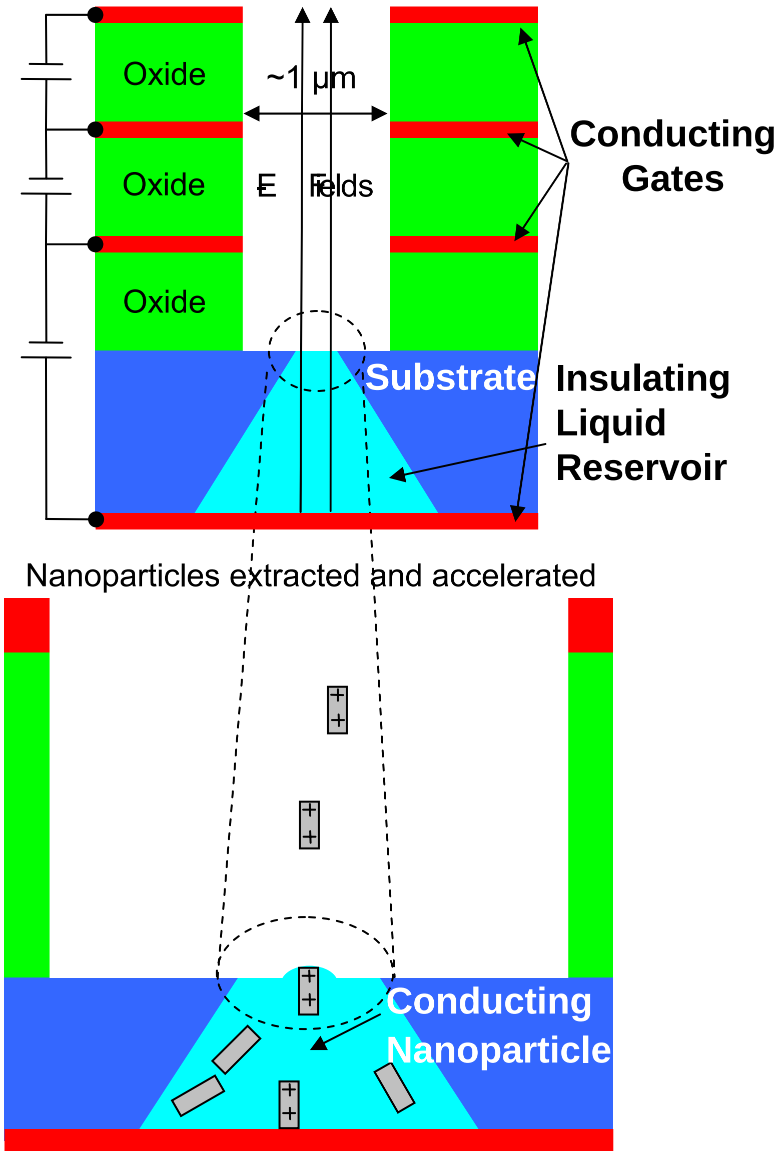
- Uses scalable array (<u>*thousands*</u> to many <u>*millions*</u>) micron-sized emitters
  - *Millions* of emitters per square cm feasible

*Use MEMS/NEMS structures for particle <u>**feed**</u>, <u>**extraction**</u>, and <u>**acceleration**</u>*



How Does nanoFET Work?

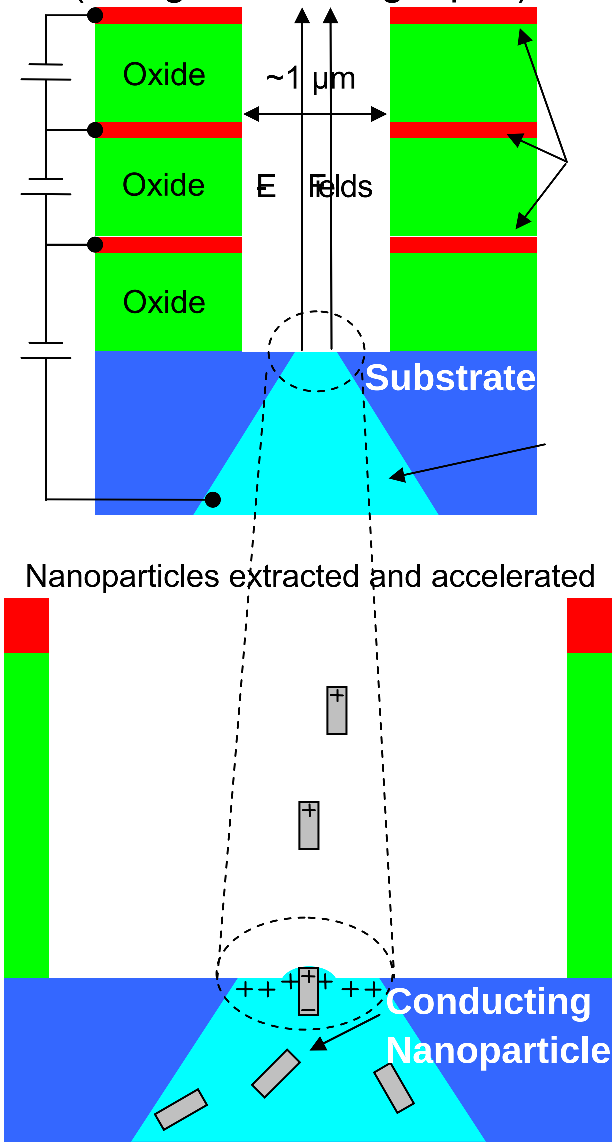
Single nanoparticle thruster emitter (using insulating liquid)



- Nanoparticles of specific size/shape immersed in low conductivity or insulating liquid carrier reservoir
- Electric field created by applying potential between extraction and accelerating electrodes
- Nanoparticles in contact with bottom electrode become charged
- Coulomb force transports charged particles to liquid surface, overcomes surface tension, extracts particles
- Extracted particles accelerated/ejected
- Note:
  - Specific charge of nanoparticles controlled by particle size, shape, and applied E- field
    - Different nanoparticles stored separately
  - Extraction with either polarity possible
    - *Neutralizer requirements simplified*

How Does nanoFET Work?

Single nanoparticle thruster emitter
(using conducting liquid)



Conducting Liquid Option

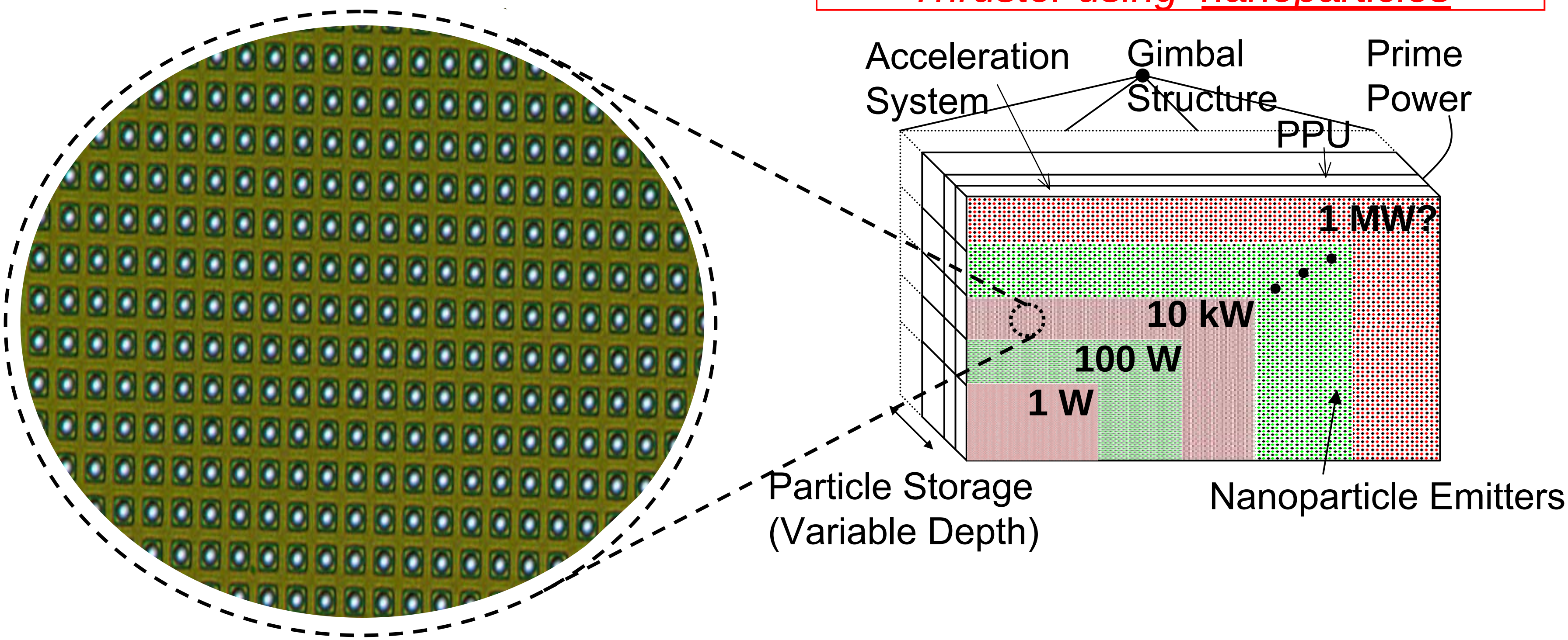
- Electric fields do not exist in the liquid
- Nanoparticles reaching liquid surface experience strong polarization charging (>than surrounding liquid)
- Particles extracted and accelerated just like insulating case

No Liquid Option

- Looking at non-liquid option

Describing the Advantages of the nanoFET Concept - nanoparticle EP System Level Picture

Flat Panel MEMS/NEMS micro-Thruster using nanoparticles

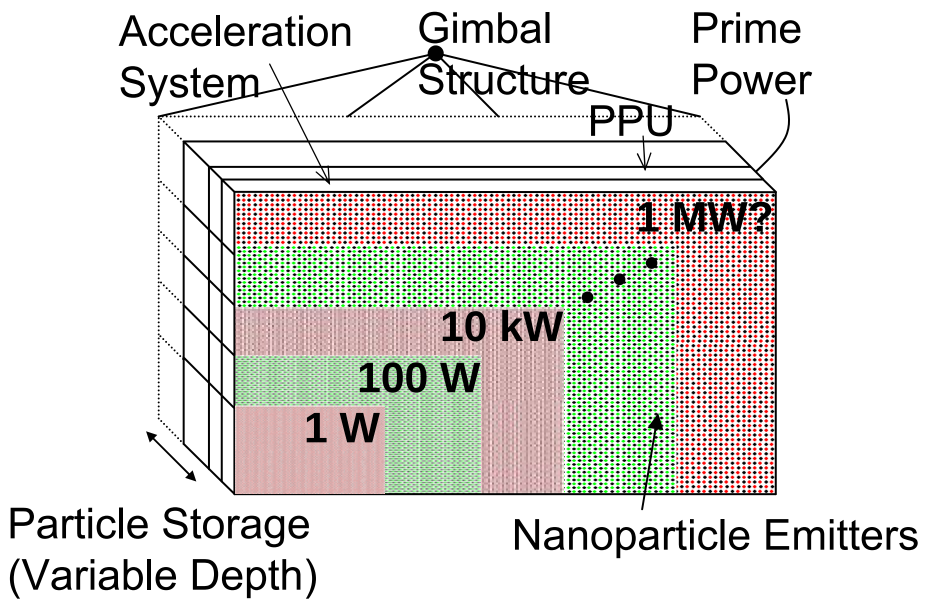


What are the advantages offered by nanoFET?

- *Affords much broader set of missions and mission phases with a single engine type*
- *Decoupling of propulsion system design from spacecraft design*
- *Propulsion system that is both mission enhancing and mission enabling*

Flat Panel MEMS/NEMS electrostatic thruster using nanoparticles

Notional Concept

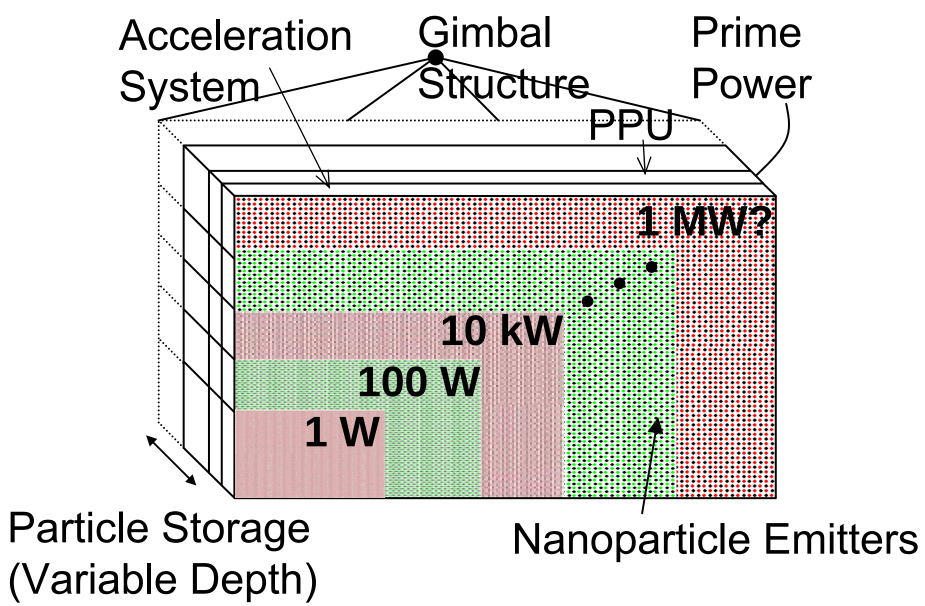


What are the advantages offered by nanoFET?

- *Affords much broader set of missions and mission phases with a single engine type*
  - Variable specific impulse over huge range (100 - 10,000 s)
  - High efficiency (~90%+) over entire specific impulse range
  - Unprecedented thrust-to-power ratios for EP due to high efficiency even at low specific impulse
- *Decoupling of propulsion system design from spacecraft design*
- *Propulsion system that is both mission enhancing and mission enabling*

Flat Panel MEMS/NEMS electrostatic thruster using nanoparticles

Notional Concept



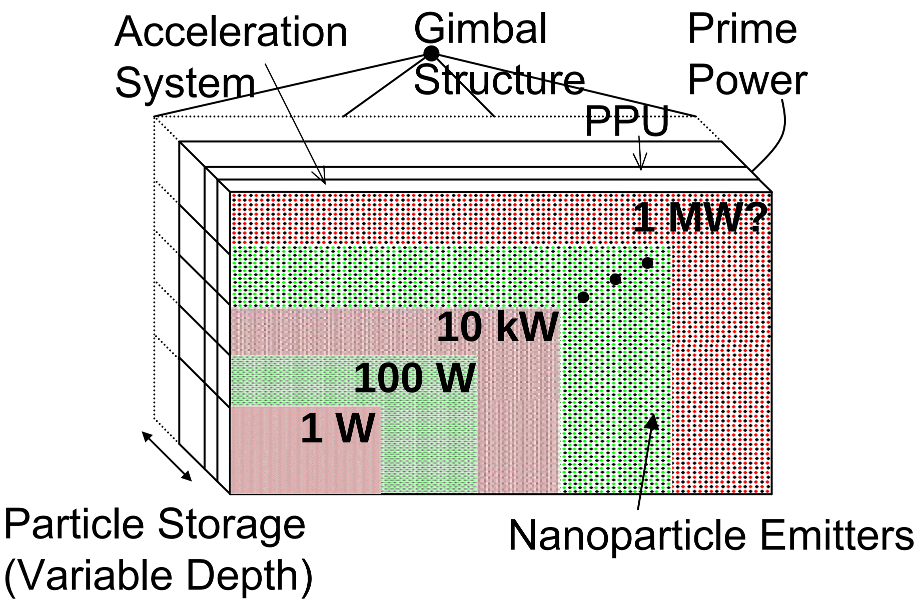
What are the advantages offered by nanoFET?

- *Affords much broader set of missions and mission phases with a single engine type*

- *Decoupling of propulsion system design from spacecraft design*
  - Scalable from watts to MWs with low thruster specific mass (kg/kW) by changing nano-accelerator array size
  - *"Plug & Play"* approach provides greater flexibility and significant cost savings to mission planners and spacecraft developers
- *Propulsion system that is both mission enhancing and mission enabling*

Flat Panel MEMS/NEMS electrostatic thruster using nanoparticles

Notional Concept



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- *Affords much broader set of missions and mission phases with a single engine type*
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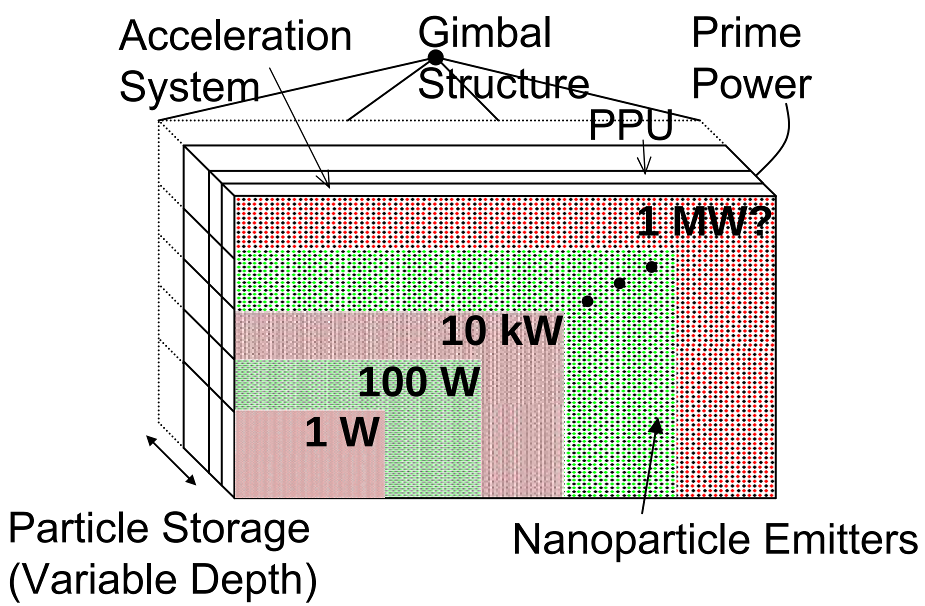
  - Improved thrust density over ion and Hall thrusters lowers specific mass
  - Improved life span over ion and Hall thrusters improves reliability and also lowers specific mass

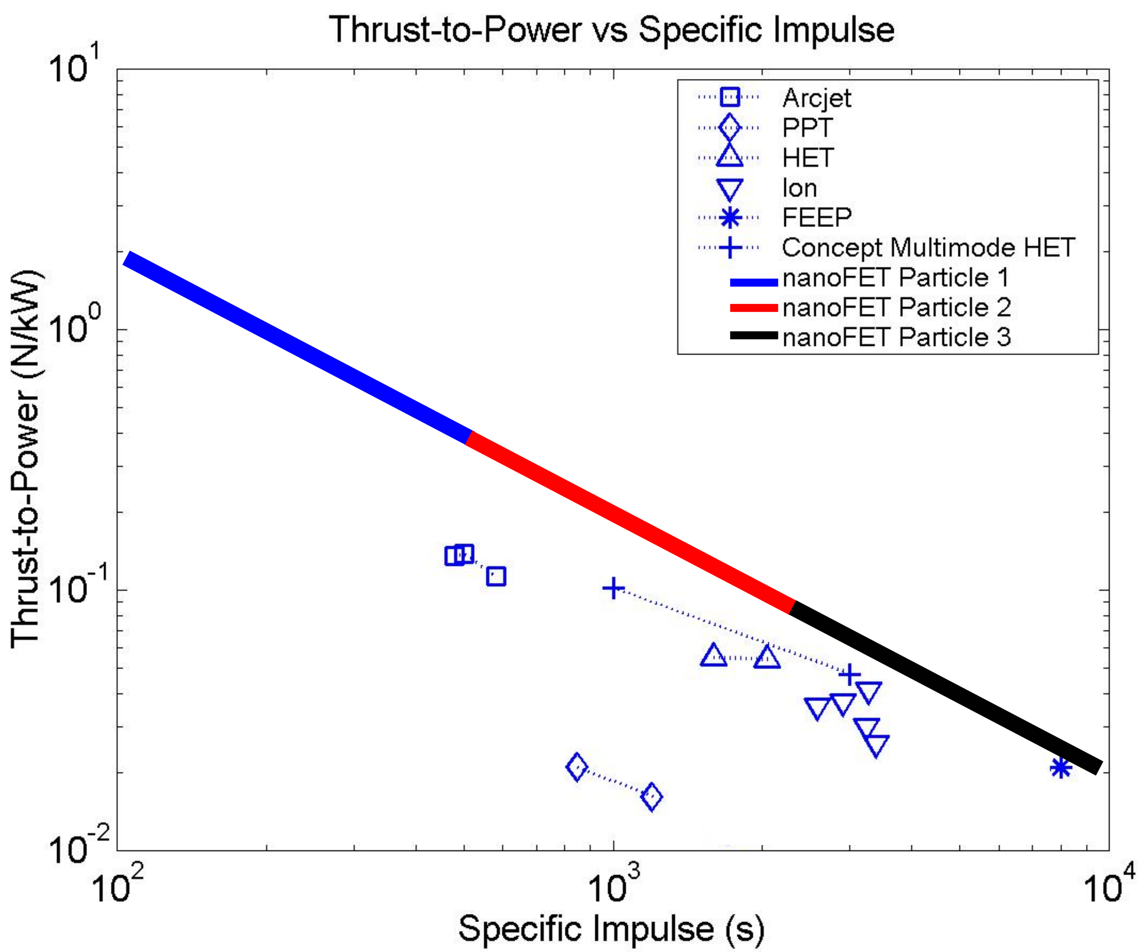
Flat Panel MEMS/NEMS electrostatic thruster using nanoparticles

Notional Concept



Nanoparticle Propulsion Compared

Highly Scalable ***Specific Impulse*** and ***Thrust-to-Power*** Using Nanoparticles (insulating liquid case)



$$I_{sp} = \frac{1}{g}\left(2V_o \frac{q}{m}\right)^{\frac{1}{2}}$$

$$\frac{T}{P} = \left(\frac{2}{V_o}\frac{m}{q}\right)^{\frac{1}{2}}$$

Particle 1
- Diameter = 5 nm
- Length = 100 nm

Particle 2
- Diameter = 1 nm
- Length = 100 nm

Particle 3
- Diameter = 1 nm
- Length = 3.5 μm

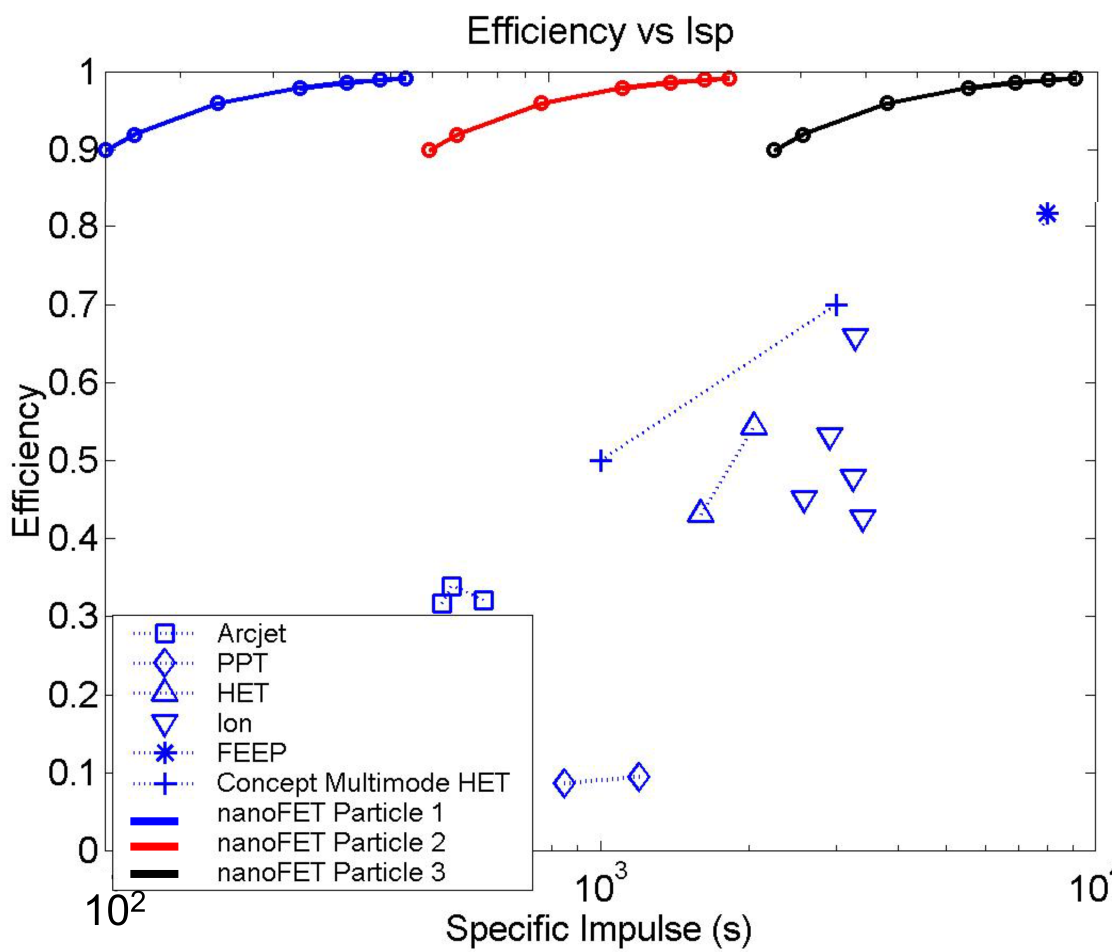
Voltage Range
- 800 – 10,000 V

Source: Wertz and Larson, 3rd Ed.

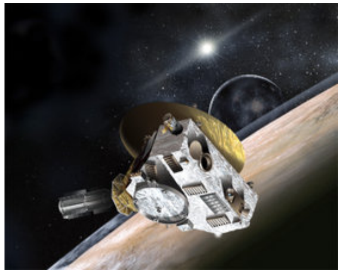
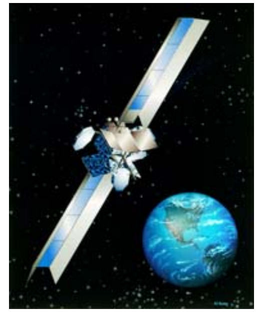
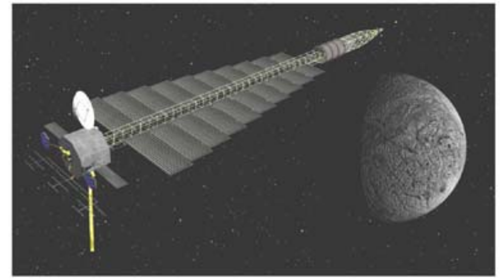
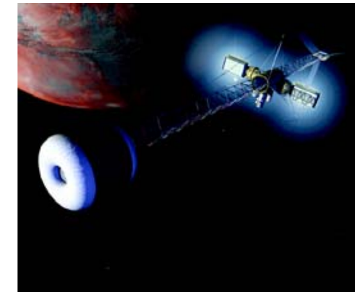
Nanoparticle Propulsion Compared: Efficiency

- Particle 1
  - Diameter = 5 nm
  - Length = 100 nm
- Particle 2
  - Diameter = 1 nm
  - Length = 100 nm
- Particle 3
  - Diameter = 1 nm
  - Length = 3.5 μm
- Voltage Range
  - 800 – 10,000 V
- Sources of Losses
  - Viscous drag
  - Charge loss to liquid
  - Particle Impingemen on gates
  - Defocusing

Improved Efficiency for entire I_{sp} Range Using Nanoparticles (insulating liquid case)



nanoFET advantages span huge range of activities

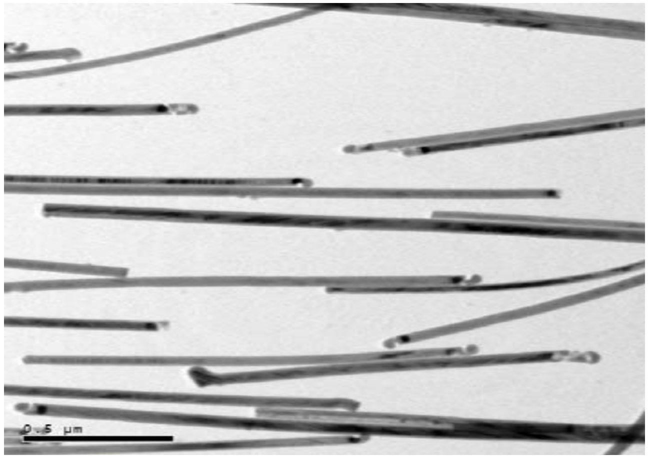
- nanoFET is geometrically scalable
  - Engine scales geometrically with power
  - Easier to ground-qualify system
- nanoFET offers wider margin for off-nominal mission scenarios
  - Example: JIMO craft enters unstable orbit around Europa and requires high emergency thrust
    - JIMO craft would be lost with ion/Hall thruster technology under extreme (but possible) scenario
    - Difference? nanoFET's ability to have T/P orders of magnitude higher than ion/Hall

- nanoFET Isp and T/P range ideal for piloted/resupply missions to Mars
  - Allows for short trip times with flexible abort scenarios
- nanoFET Isp and T/P range ideal for Earth orbit
  - Enables dynamical re-tasking of space assets
  - SINGLE engine type for most satellites (nanoSATs to very large space stations and space tugs)
    - Decouples propulsion and satellite design

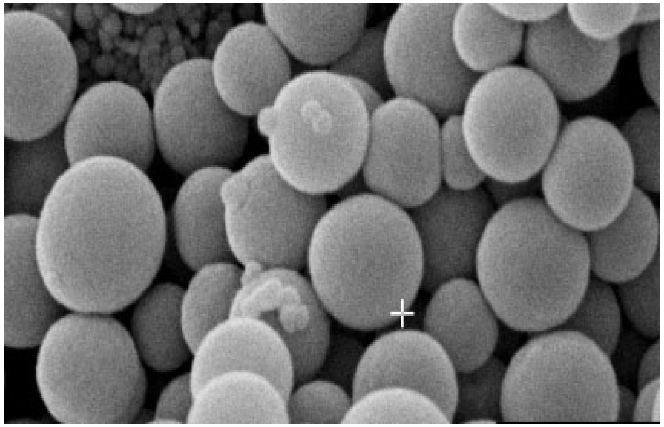
Nanoparticles

- Pre-fabricated conducting nano-particles (wires or spheres)
- Different sizes and shapes used for different performance needs
- Particle sizes from ~1 nm to microns
- Potential particles today
  - Carbon nano-tubes (CNT)
  - Metal spheres and wires
  - Silicone wires fused with nickel
  - Fullerenes
- Considerations
  - Wettability
  - Variability in particle dimensions
  - Contamination
  - Quantum effects
  - Adhesion between nanoparticles and bulk surfaces

Nano-wires approximately 45 nm dia. [1]



Nano-spheres in 100 nm dia. range [2]

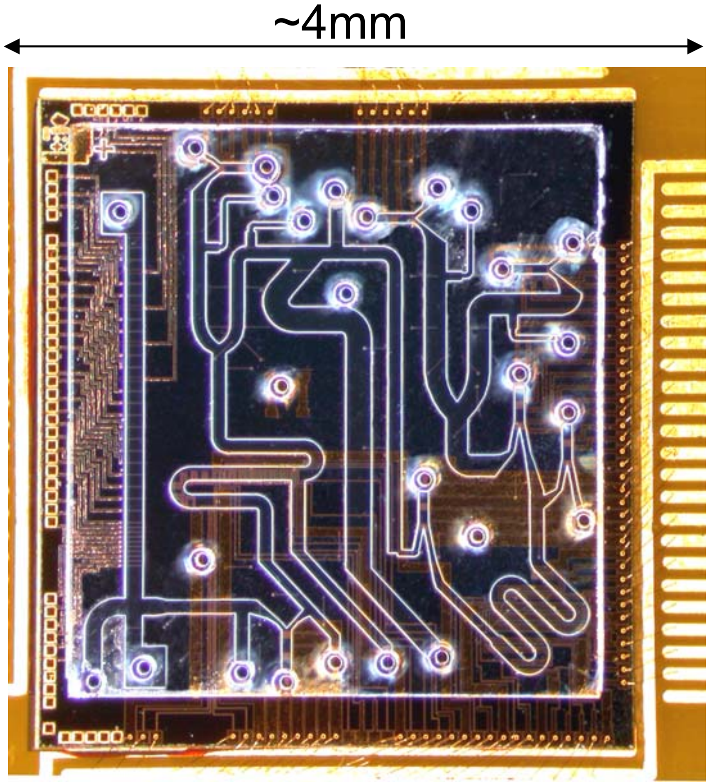


1. Koninklijke Philips Electronics. "www.research.philips.com/newscenter/pictures/ldm-nanotech.html
2. Behan, N. "Nanomedicine and Drug Delivery," www.ul.ie/elements/Issue4/behan.htm

Microfluidics & Nanoparticle Transport

- NanoFET needs
  - Nano-particles transport to extraction zone
  - Liquid recirculation
  - Conductive particles transport to liquid surface to be extracted
- Related research work
  - Bio-MEMS and miniaturized chemical reactors
  - No fundamental infeasibility issues
- Possible transport methods
  - Pressure gradients and peristalsis
  - Capillary effects
  - Electrokinetics
  - Lorentz forces
  - Acoustic streaming

Influenza genotyper chip (Burns, UM)

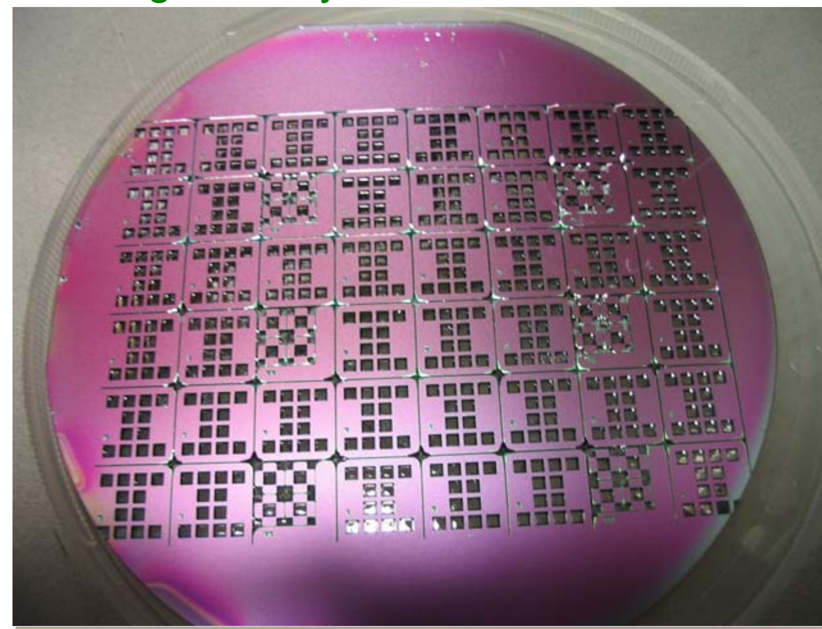


- Considerations
  - Minimize particle wetting upon extraction
  - Minimize wetting of gated structures

MEMS Gate Structure

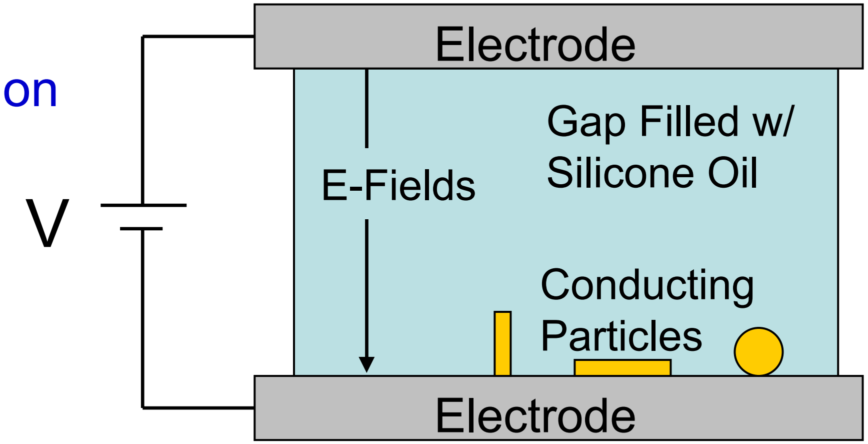
- Gates provide electric field to extract and accelerate nanoparticles
- Stacked gate design permits decoupling of extraction and acceleration stages
- Different gated regions may be biased to opposite polarity to provide charge neutralization
- Current gate design: beta version
  - 2-micron dielectric thickness
  - 3.4E5 emission holes per 1-cm^2 device
  - 2-micron diameter emission holes spaced 5-microns center-to-center

MEMS gate array on 4-in diameter Si wafer



nanoFET Experiments

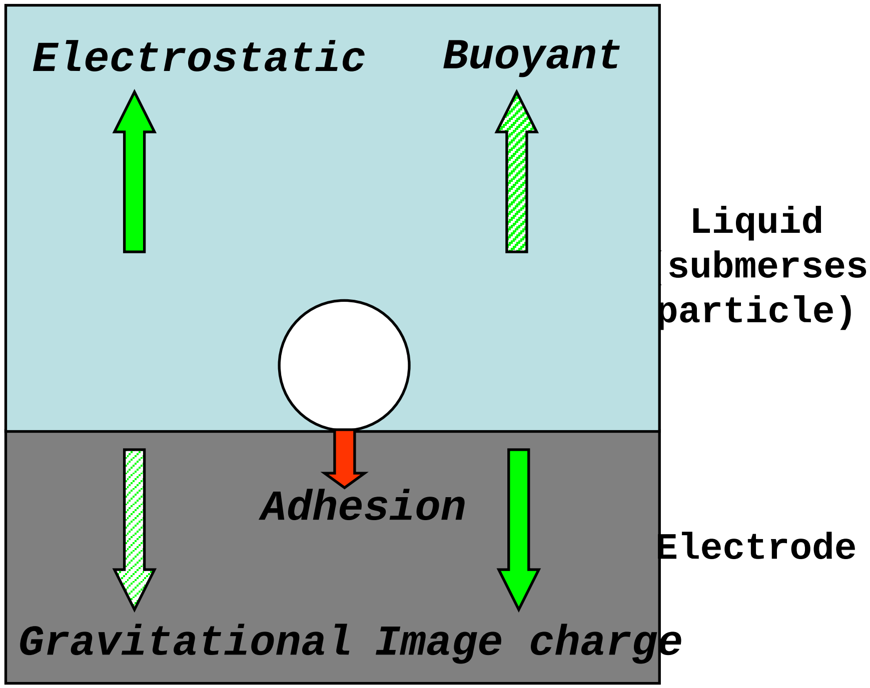
- Purpose of proof-of-concept experiments in insulating liquid
  - Understand how nanoFET concept works at *scaled-up* dimensions
  - Validate models of particle behavior and Taylor cone formation in large electric fields
- Experiments conducted
  - Particle lift-off and oscillation
  - Particle extraction
  - Taylor cone formation threshold
  - Vacuum operation
- Prove feasibility of particle extraction
  - Through liquid surface
  - Through grid structure
  - Prior to Taylor cone formation
  - In vacuum environment
- Planned future tests
  - Conductive liquid
  - Nanoparticles



Particle Lift-Off

- Lift-off forces
  - electrostatic force in liquid
  - buoyant force
    - vanishes in zero-g
- Restraining forces
  - gravitational force
    - vanishes in zero-g
  - electric image force
    - reduces net electric field on particle
  - adhesion force between particle and electrode
    - significant for particle sizes on order of electrode surface roughness

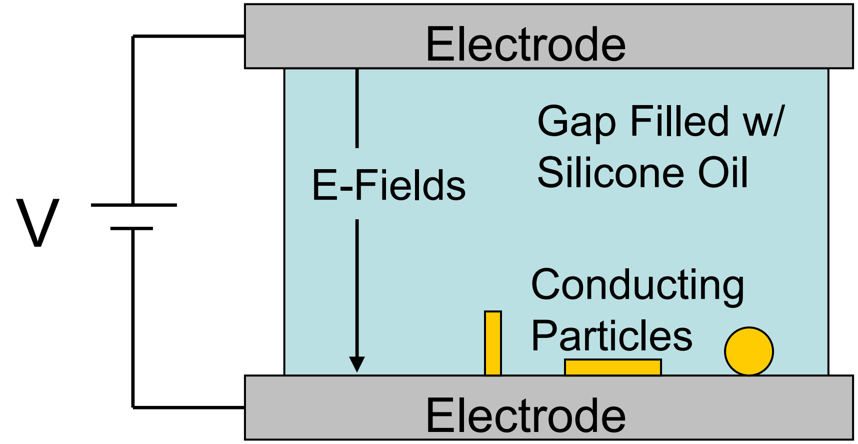
$$q_{sph} = \frac{2\pi^3}{3} r^2 \varepsilon_\ell E_\ell , \qquad q_{cyl} = \frac{\pi \ell^2 \varepsilon_\ell E_\ell}{\ln\left(\frac{2\ell}{r}\right) - 1}$$



Particle Oscillation Experiments

- Demonstrate conductive particle lift-off and motion in insulating liquid due to E-fields
- Particles: aluminum
  - spheres (800-micron dia.)
  - cylinders (300-micron dia. by 1.5-mm length)
- Liquid: 100 cSt silicone oil

Experimental Setup: Liquid filled electrode gap with conducting particles

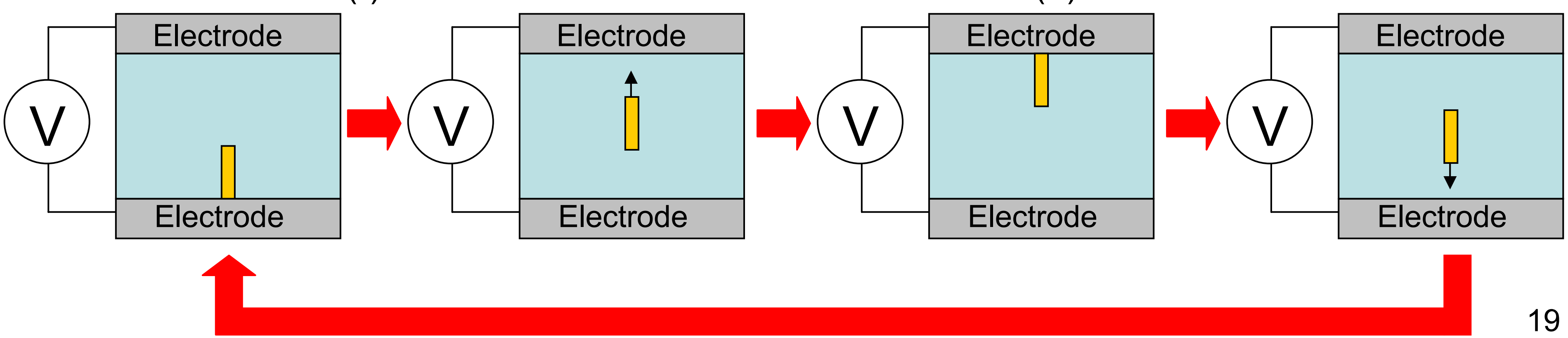


1. Charged on bottom electrode (-)

2. Transported to top electrode

3. Charged on top electrode (+)

4. Transported to bottom electrode

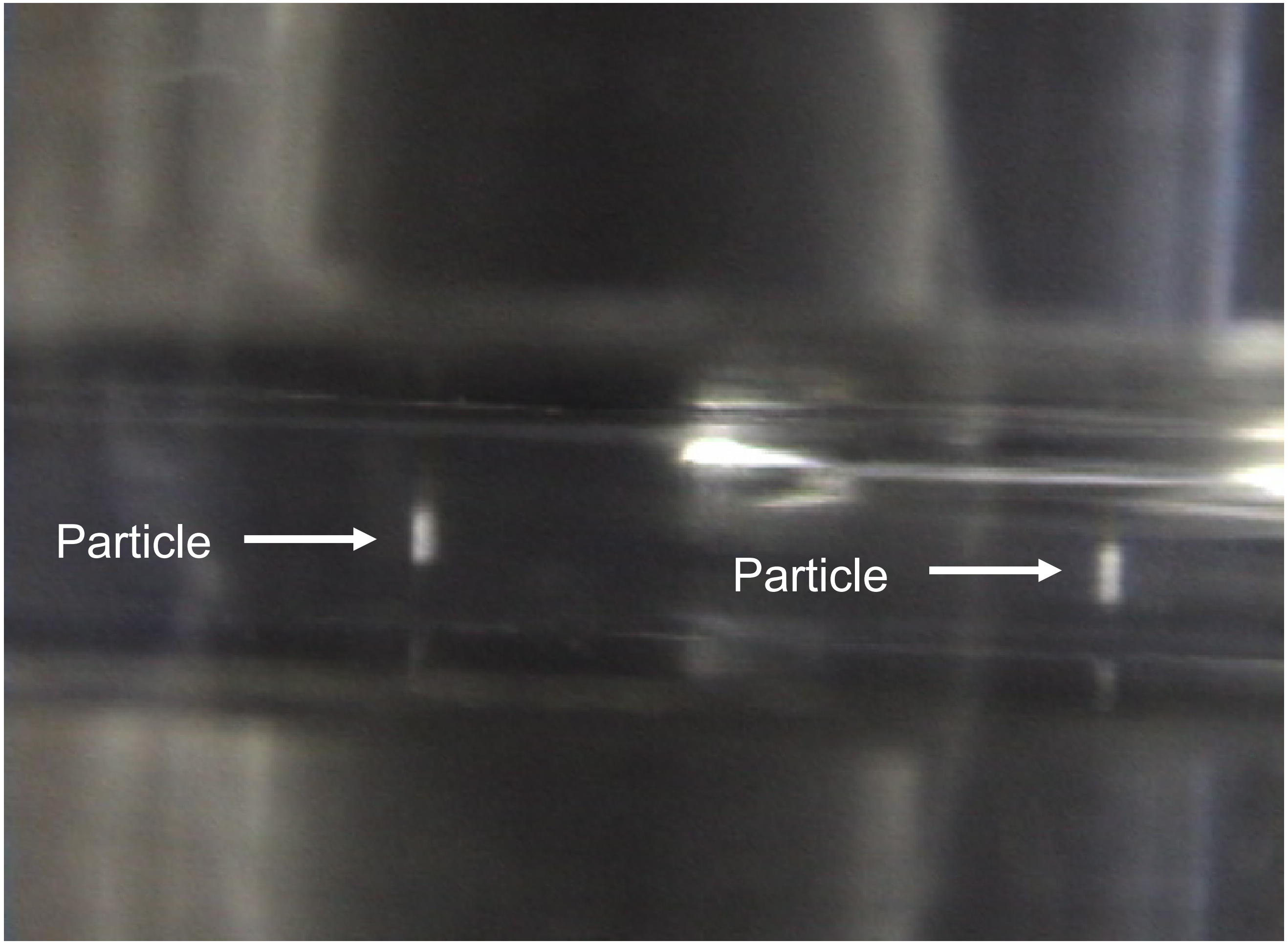


Particle Oscillation Video

- Cylindrical
  - diameter = 300 μm
  - length = 1.5 mm
  - gap = 6.35 mm
  - V ~ 5 kV

Top Electrode

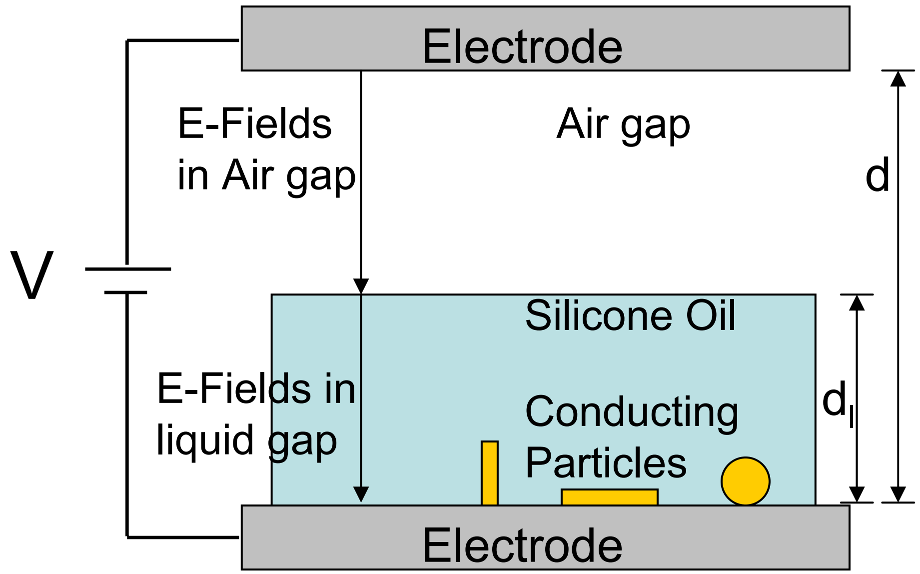
Bottom Electrode



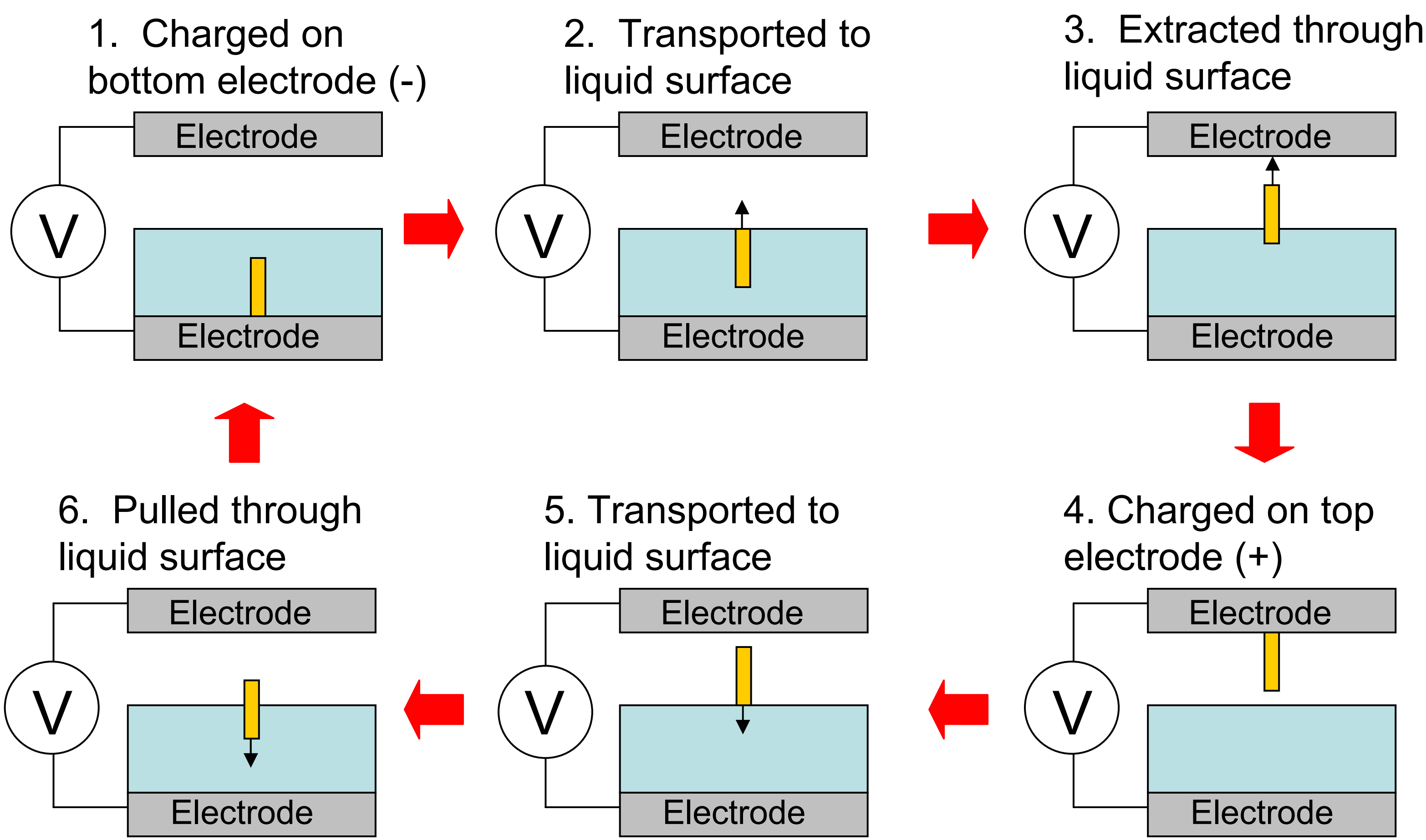
Particle Extraction Experiments (I)

- Experiments to demonstrate
  - conductive particle extraction through insulating liquid surface due to E- fields
  - feasibility of particle extraction prior to formation of Taylor cones
- Particles: aluminum
  - spheres (800-micron dia.)
  - cylinders (300-micron dia. by 1.5-mm length)
- Liquid: 100 cSt silicone oil
- Results: Particles of same kind extracted with approx same E-field strength independent of liquid height
  - Terminal velocity reached prior to extraction
  - Negligible charge loss in fluid

Experimental Setup: Partially liquid filled electrode gap with conducting particles

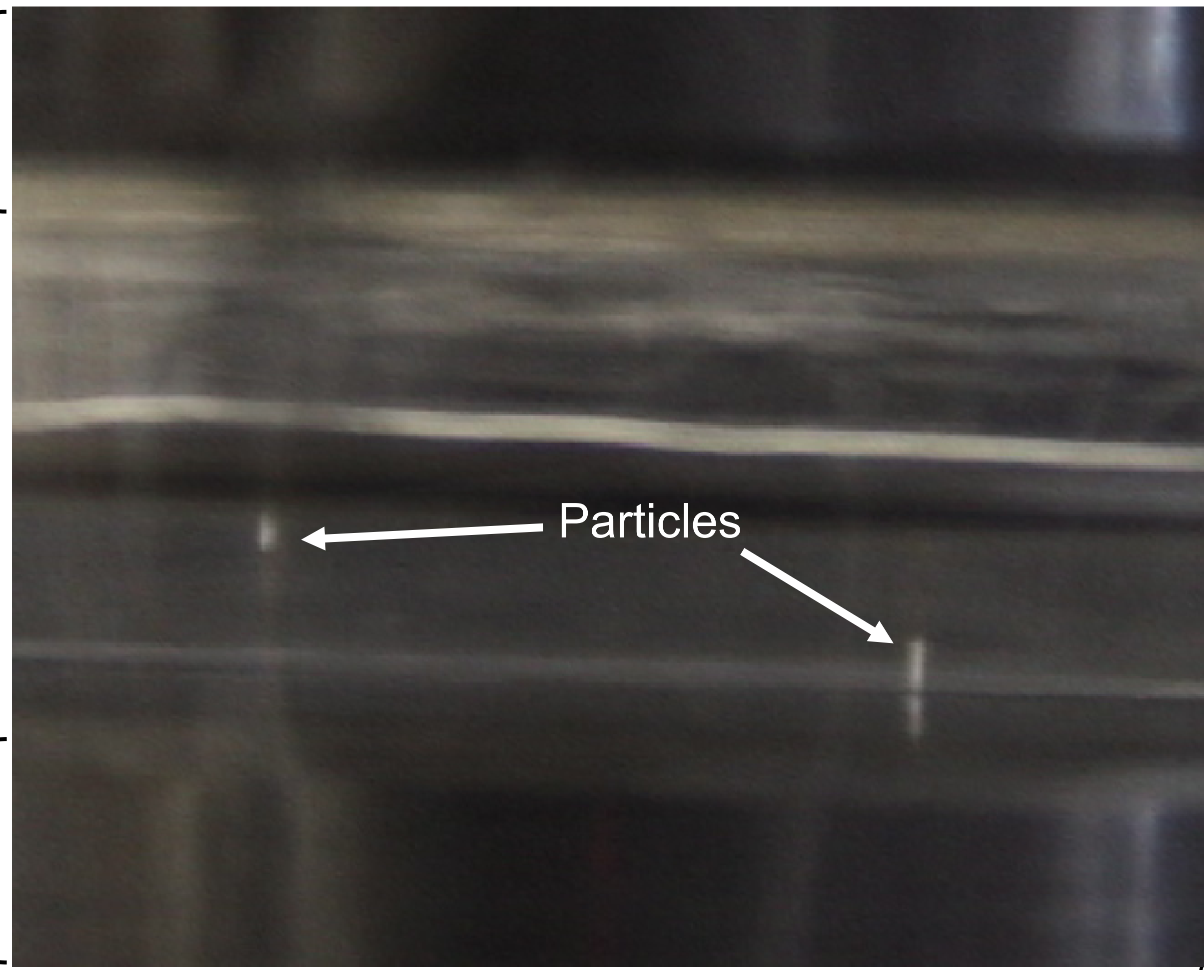


Particle Extraction Experiments (II)



Particle Extraction Video

- Cylindrical Particle
  - diameter = 300 μm
  - length = 1.5 mm
  - gap = 12.7 mm
  - liquid thickness = 5 mm
  - V ~ 14 kV

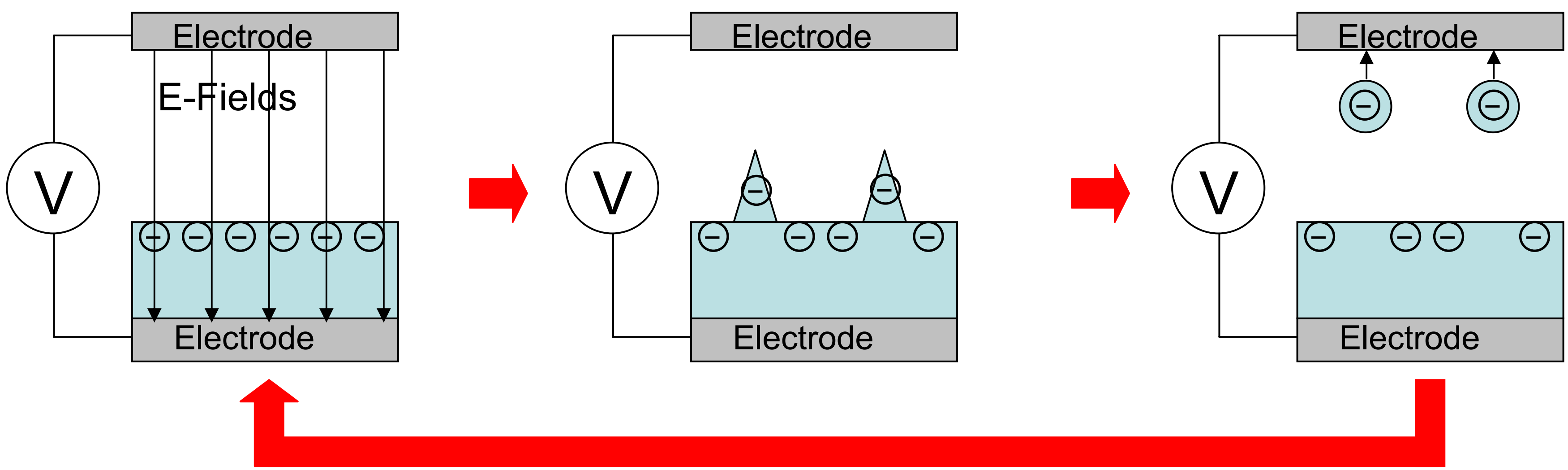


Taylor Cone Formation

- Electric field acts to pull free charges from the liquid
- Surface tension acts to keep charge within liquid
- Cones form as a result of balance of forces
- Strong enough E-field pulls cones to top electrode

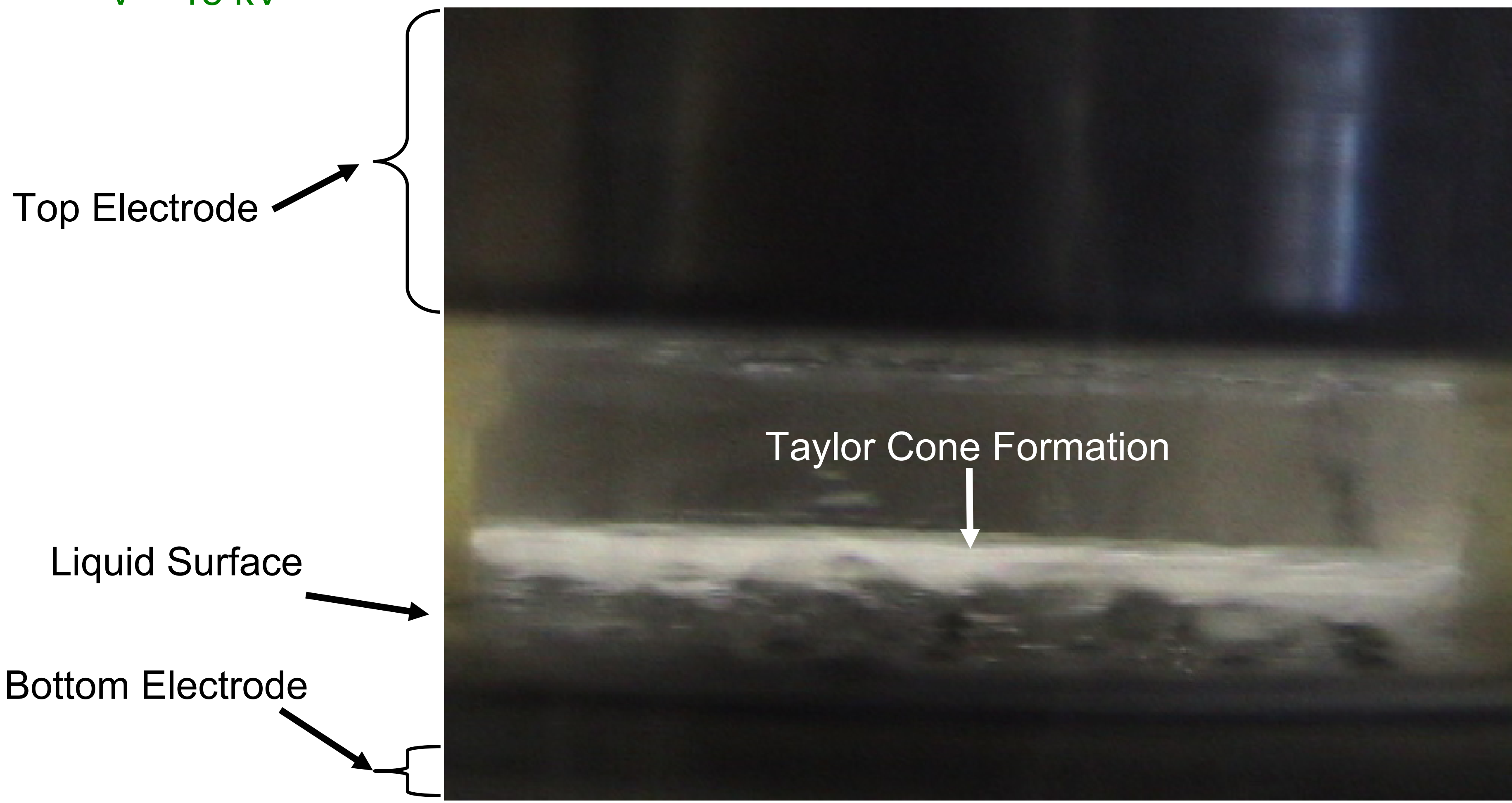
$$E_{\min} = \left(\frac{4 g \gamma \rho_\ell}{\varepsilon_0^{\;2}} \right)^{\frac{1}{4}} \left[1 + \left(\frac{\varepsilon_0}{\varepsilon_\ell} \right)^2 \right]^{-\frac{1}{2}}$$

1. Charge pulled to surface
2. E-field pulls liquid up, surface tension pull down
3. Charged droplets are pulled off surface



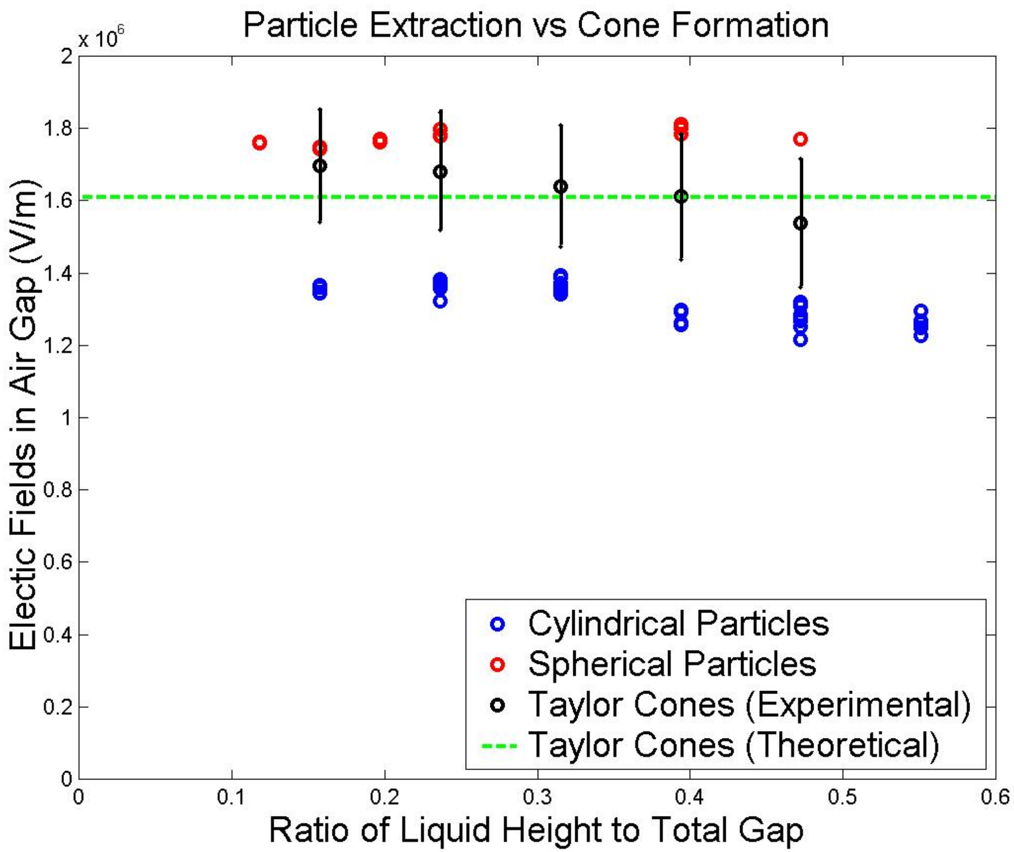
Video of Taylor Cone Formation

- gap = 12.7 mm
- liquid thickness = 5 mm
- V ~ 18 kV



Taylor Cone Formation vs. Particle Extraction

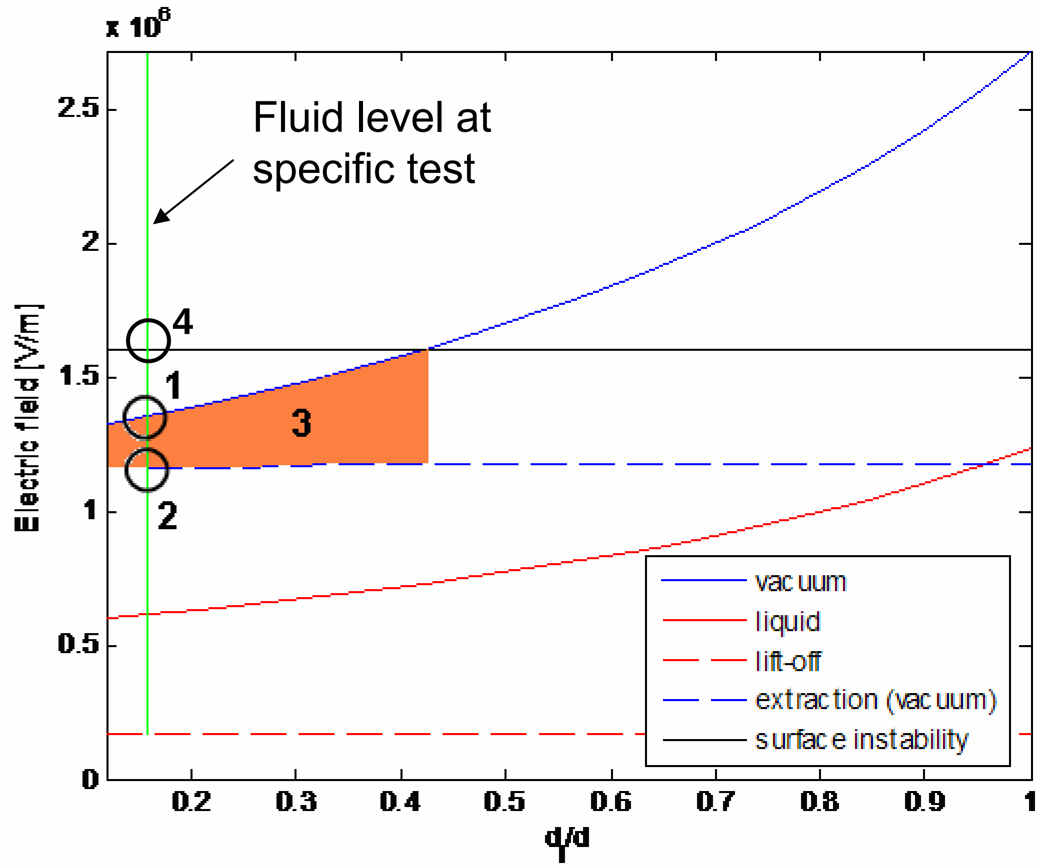
- What do Taylor cones mean to nanoFET?
  - Formation of Taylor cones could mean problems for nanoFET because liquid could be emitted along with particles
  - Is there a regime where particles are extracted and cones do not form?...



- Spherical Extraction
  - average extraction E-field = 1.78E6 V/m
- Cylindrical Extraction
  - average extraction E-field = 1.32E6 V/m
- Cone Formation
  - average cone formation E-fields = 1.63E6 V/m
- …Experimentally demonstrated a regime where particles can be extracted before cone formation begins!

Feasible Design Space

- Theory shows regimes exist for particle extraction *prior* to Taylor cone formation
- Excellent agreement between Taylor cone formation experiment and theory
- Preliminary model under predicts particle extraction field by 20%
  - Requires better understanding of particle field enhancement at liquid surface
  - Requires better understanding of surface tension effects on particle

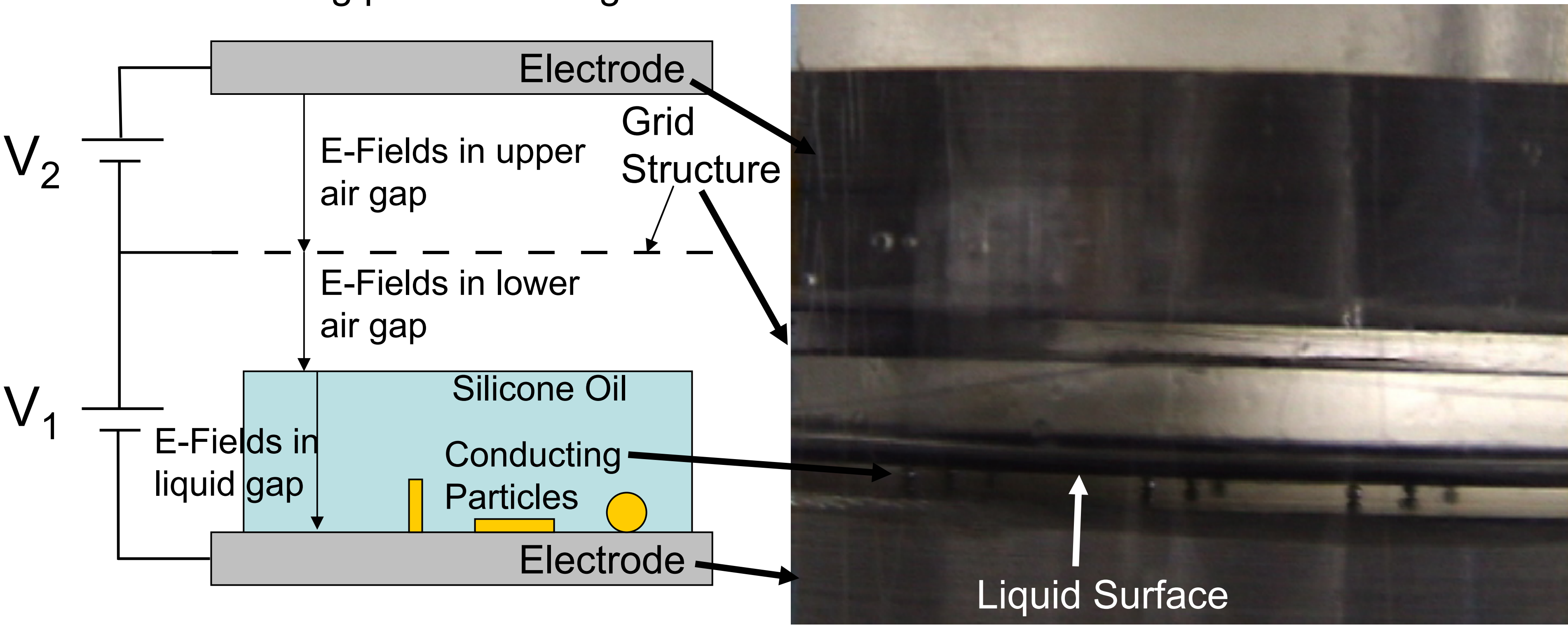


1. Particle extraction (experiment)
2. Particle extraction (theory)
3. Feasible design space (theory)
4. Taylor cone formation (experiment and theory)

Particle Extraction Through Grids

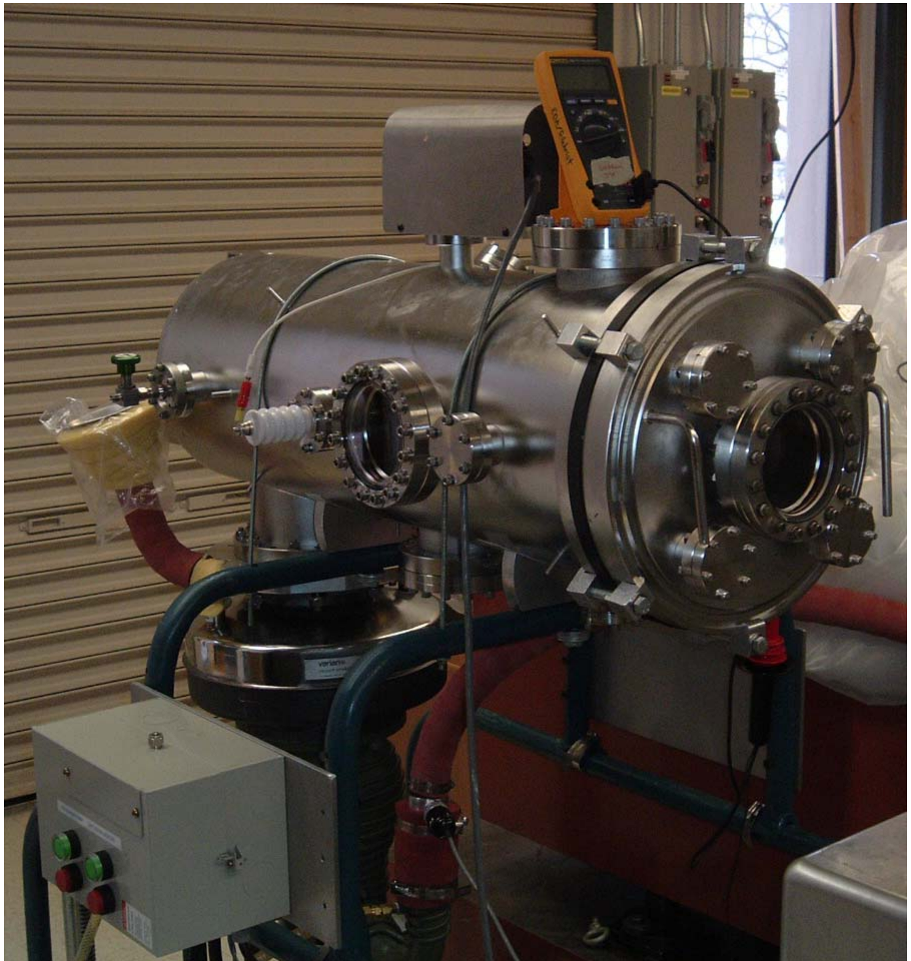
- Demonstrate extraction of conducting particles from insulating liquid by electric fields through a grid structure

Experimental Setup: Partially liquid filled electrode gap with conducting particles and grid



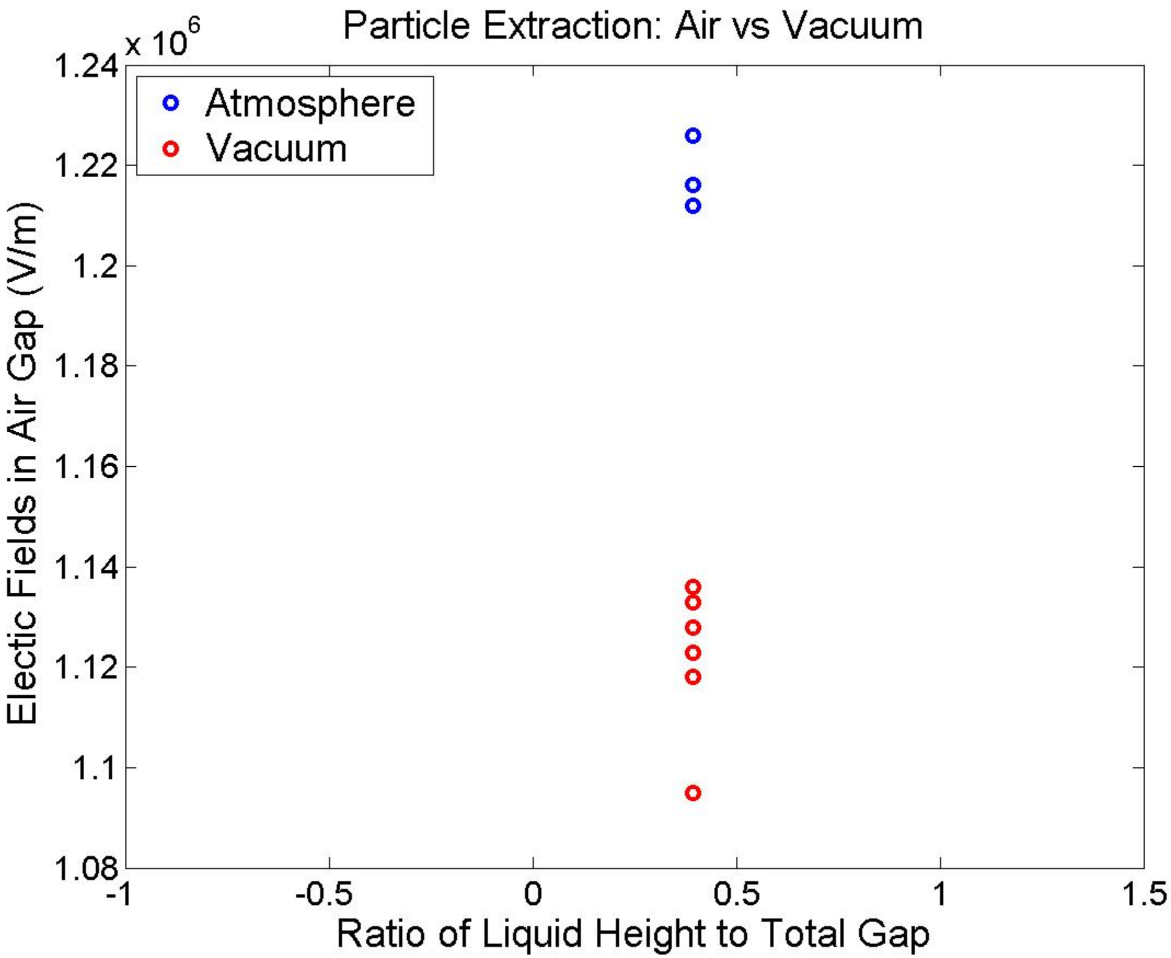
Particle Extraction in Vacuum (I)

- Our new vacuum chamber:
  - Pumps: Diffusion and Roughing
  - Ultimate Pressure ~ 10^{-7} Torr



Particle Extraction in Vacuum (II)

- Expect E-fields required for particle extraction to be same when at atmosphere or in vacuum, but somewhat better in vacuum



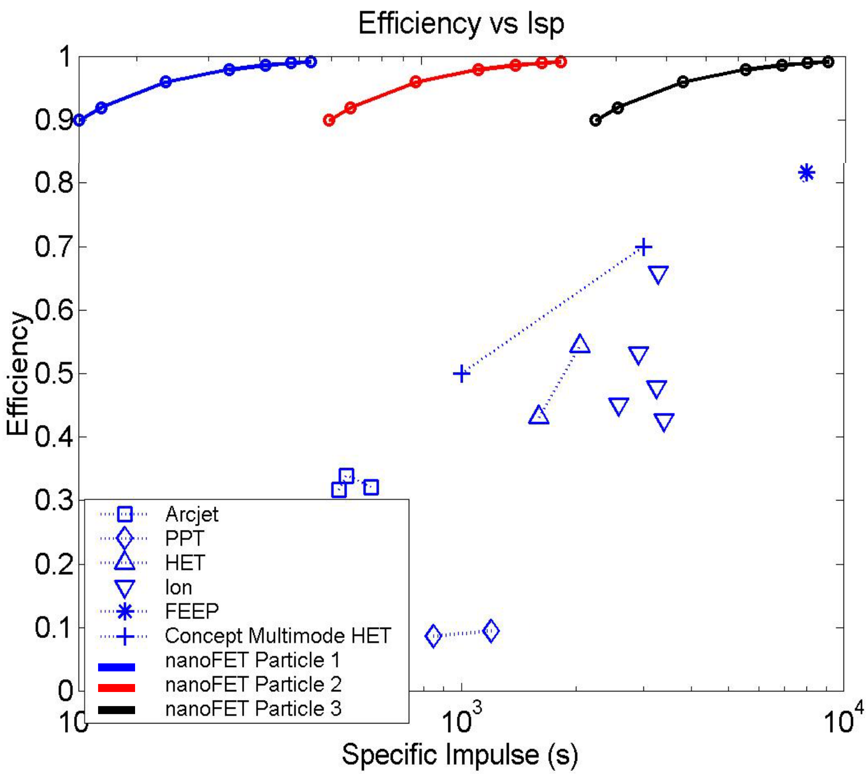
- Setup
  - Al Cylinders
    - d = 300 μm
    - l = 1.5 mm
  - Gap = 12.7 mm
  - Silicone Oil
    - 5.0 mm thick
- At atmosphere
  - P = 760 Torr
  - E_{av} = 1.22E6 V/m
- In Vacuum
  - P = 2.5E-5 Torr
  - E_{av} = 1.12E6 V/m

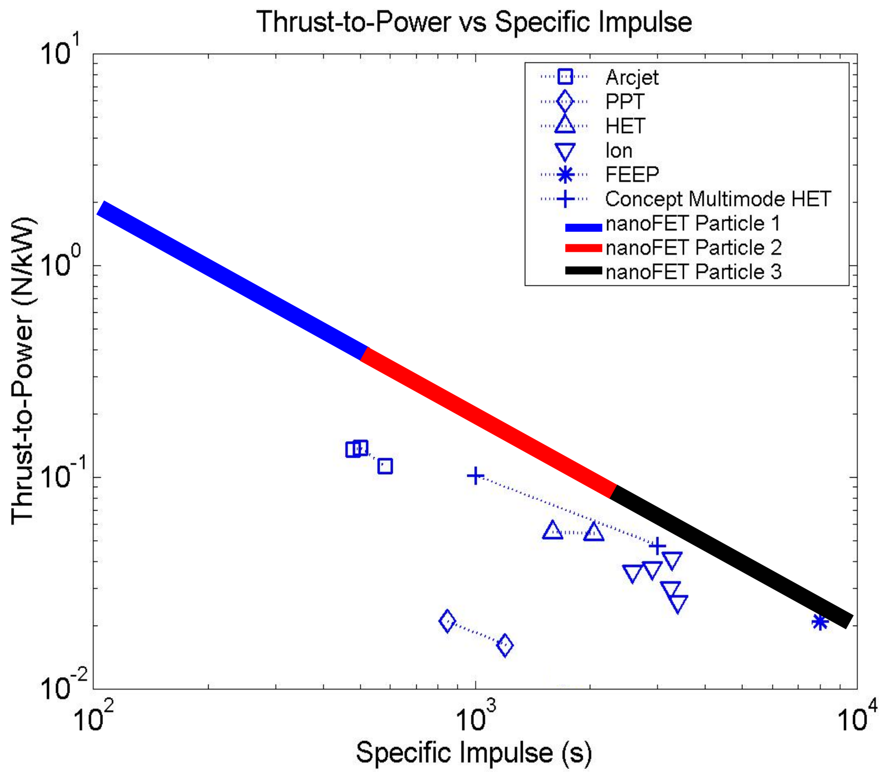
Looking to the Future

- Quantify vacuum environment performance (understand differences)
- Scale experiments to smaller dimensions
- Research full range of nanoparticle options
- Identify particle transport options
  - Micro-fluidic Bio-MEMS and Chemical analysis technology *synergism*
  - Non-fluid options
- MEMS/NEMS structures
- Refine a more complete integrated system concept
- More quantified assessment of mission scenarios

Nanoparticle EP Concept Appears Feasible

New Paradigm: High Efficiency over tremendous Isp and T/P





- *Broad set of missions - mission phases with single engine type*
- *Decouples propulsion system and spacecraft design*
- *nanoFET is both mission enhancing and mission enabling*