SAND2007-3570C

Electrokinetically Pumped Liquid Propellant Microthrusters for Orbital Station Keeping

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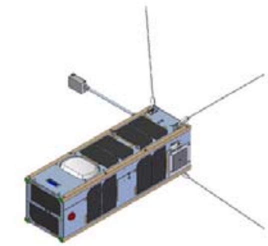
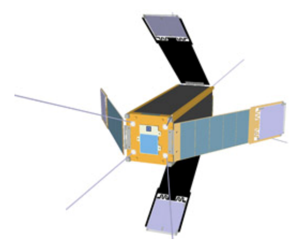
Background & Motivation

- Small satellites for research
  - Nanosatellites <10 kg
  - Picosatellites <1 kg
- Why small satellites?
  - Low cost to orbit
  - Standard designs (CubeSat)
  - Multi-satellite experiments
  - Academia, industry, civilian space agencies
- Importance of propulsion system performance
  - Defines mission duration
  - Stabilizes orbital trajectory
  - Enables advanced capabilities
    - Formation-flying
    - Extravehicular inspection
    - Precision pointing

U. Aachen - COMPASS-1
1.0 kg, 10x10x10 cm



U. Toronto - CanX-2
3.5 kg, 10x10x34 cm



T. U. Delft - Delfi-C3
3 kg, 10x10x30 cm

NASA - Mini AERCam
4.5 kg, 20 cm dia.

NASA - GENESAT-1
4.5 kg, 12x12x36 cm

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Microthruster Performance Metrics

- Maximum thrust

$$F_T = m_{sc} a_{sc} = -m_{prop} a_{gas} = -\dot{m}_{prop} v_{exit}$$

- Delta-V (total impulse)

$$I_{tot} = \int F_T(t)dt \approx m_{sc} \Delta V$$

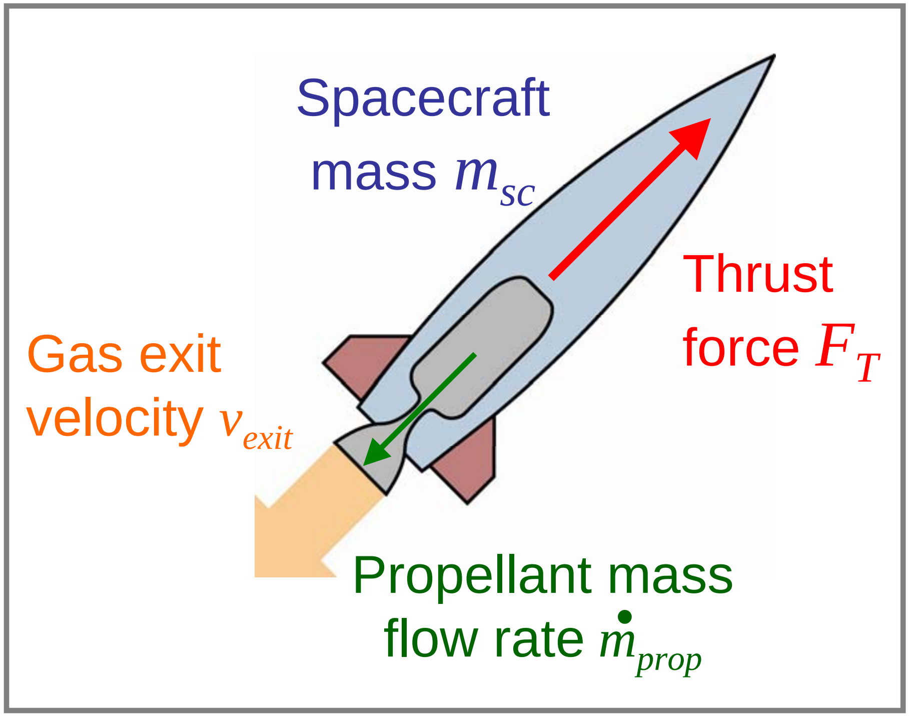
- Impulse bit (resolution)

$$I_{bit} = F_{T-\min} t_{\min}$$

- Specific Impulse (efficiency)

Continuous $$I_{sp} = \frac{F_T}{\dot{m}_{prop} g_0} = \frac{v_{exit}}{g_0}$$

Pulsed / Digital $$I_{sp} = \frac{\int F_T(t)dt}{m_{prop} g_0}$$



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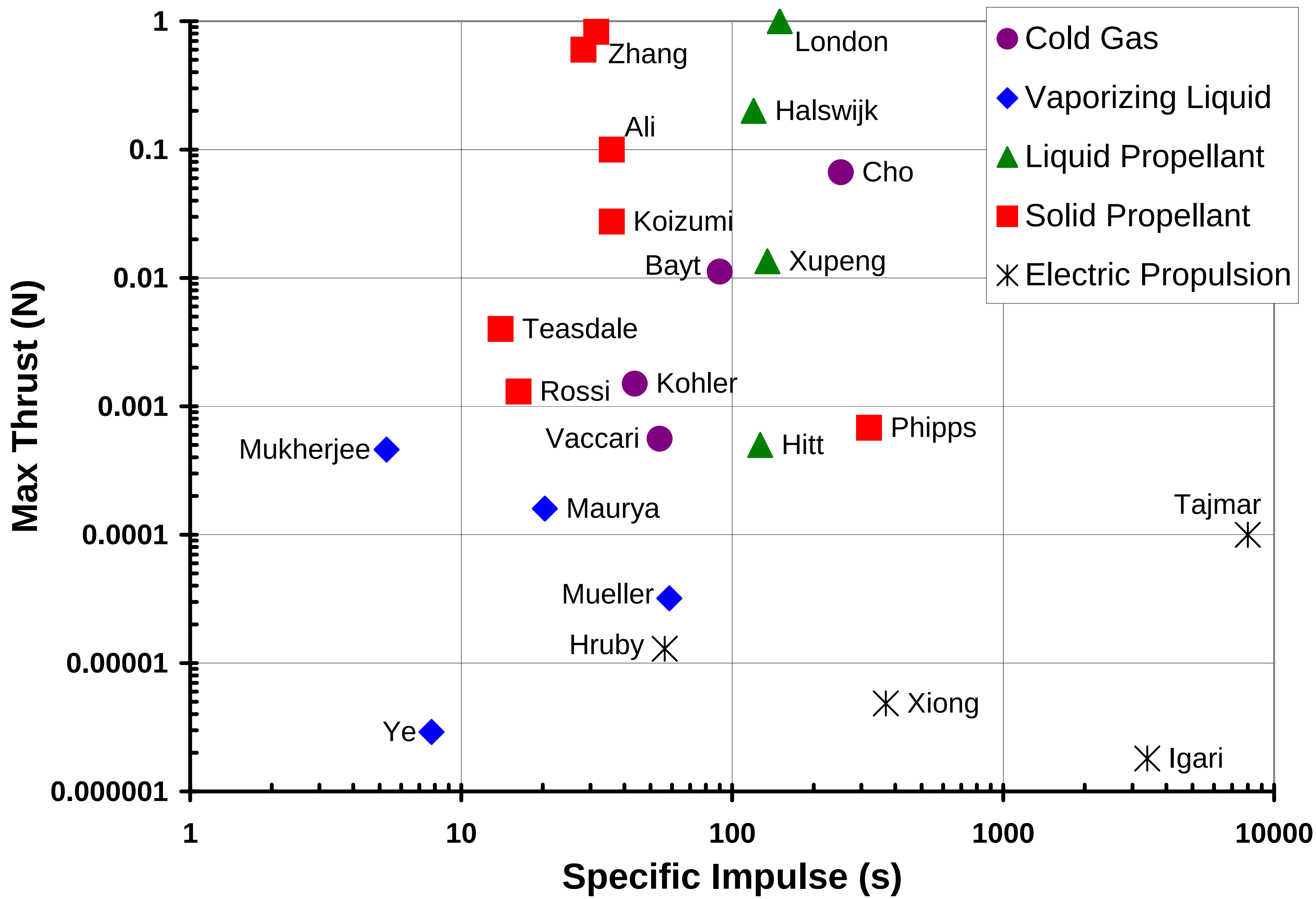
Thrust Requirements for Small Satellite Maneuvers

Mission	Mission Time	Thrusting Time	ΔV (m/s)	Thrust (μN/ kg)
Increase altitude from 700 km to 701 km	0.82 hours (half orbit)	10 min.	0.53	880
	2 days	2 days	0.53	3.1
Move 10 km ahead at 700 km altitude	3.3 hr. (two orbits)	40 min.	1.1	460
	2 days	40 min.	0.04	17
Change inclination by 1° at 700 km altitude	0.82 hours (half orbit)	10 min.	131	220,000
	2 days	12 hours	131	3,000
De-orbit from 700 km (Hohmann transfer)	0.80 hours (half orbit)	10 min.	160	270,000
De-orbit from 700 km (Low-Thrust Spiral)	1 week	1 week	330	550
Change inclination by 1° at GEO	12 hours (half orbit)	10 min.	54	9,000
	1 week	1.75 days	54	360
North-South Station-Keeping at GEO	1 week	20 min.	0.96	800
Boost altitude by 100 km at GEO	12 hours (half orbit)	10 min.	3.65	6,100
	1 week	1 week	3.65	6

S. W. Janson, H. Helvajian, W. W. Hansen, and J. Lodmell, "Microthrusters for nanosatellites," in *2nd Intl. Conf. on Integrated Micro Nanotechnology for Space Applications (MNT99)*, Pasadena, CA, USA, 1999.

Recent Microthruster Publications



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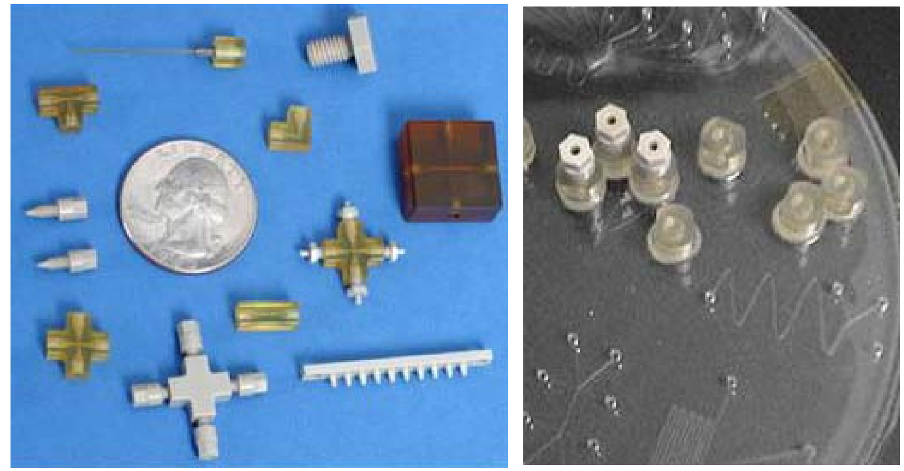
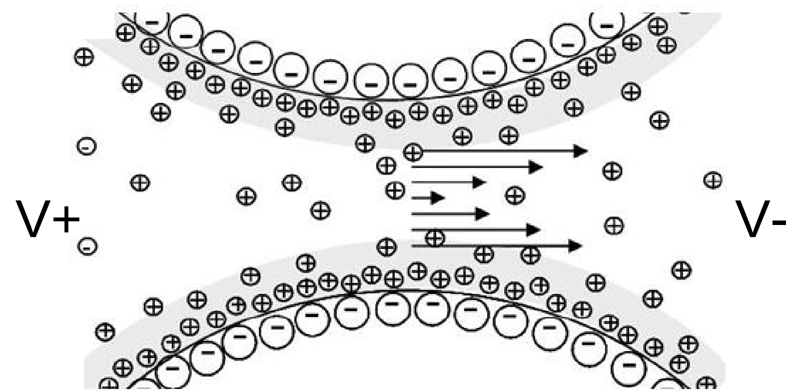
Bioanalysis to Microthrusters?

- Leverage technology & capabilities devloped through Sandia bioanalysis work
- CapTite™ capillary fittings and interconnects
  - Low dead volumes
  - Chemical resistance
  - Seals up to 35 MPa
  - Automated valves / pumps



CapTite™ fittings and chip interface components

- Integrated electrokinetic (EK) pumping
  - Direct voltage control
  - No moving parts
  - Pulse-less flow
  - Pressures up to 700 MPa at stagnation



Electrokinetic Pumping

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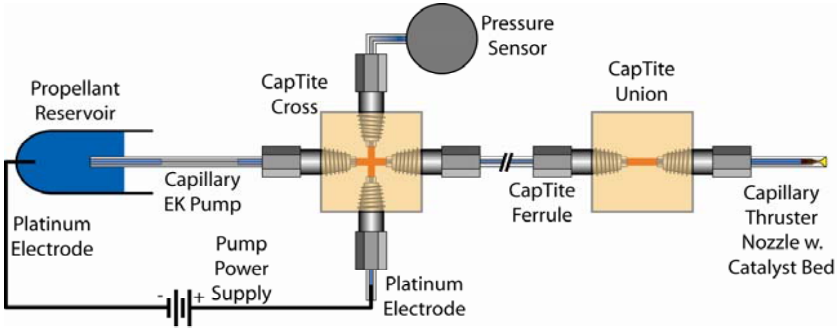
Integrated Electrokinetic Pumping

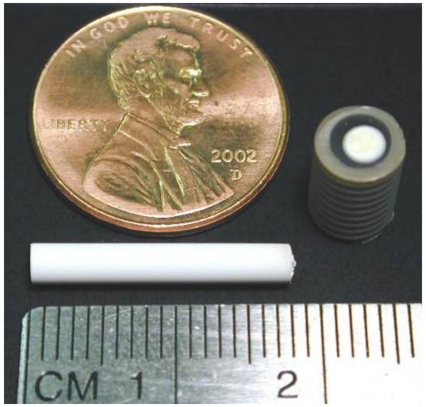
Capillary EK Pump

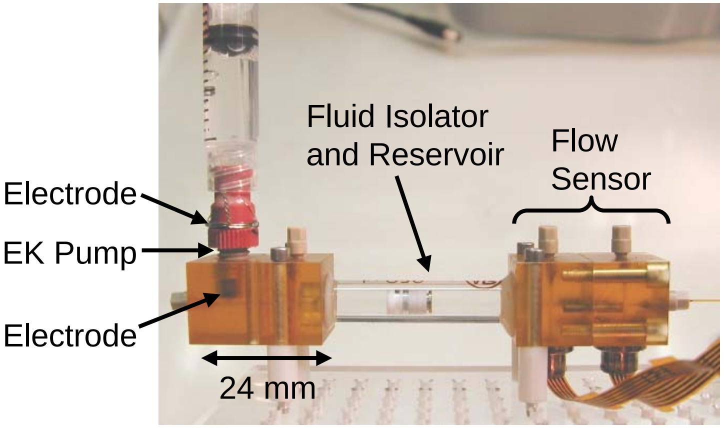
20 MPa or 650 nL/min



Large Format Sintered-monolith EK pump

8.3 MPa or 170 µL/min





Large format EK pump for indirect fluid metering

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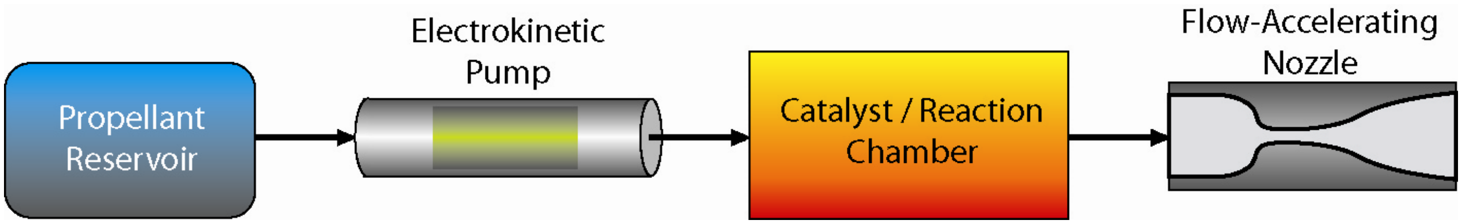
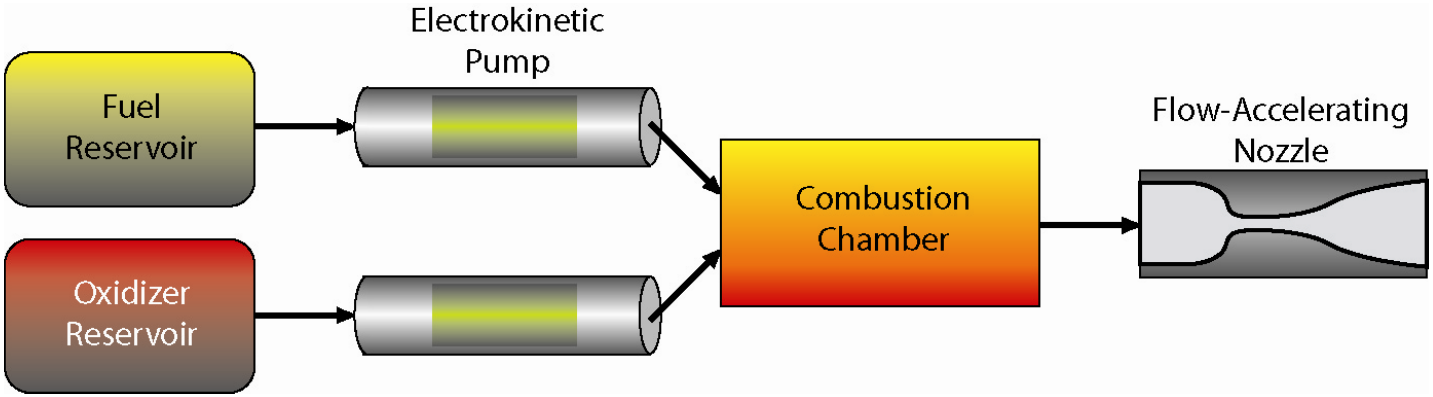
Liquid Propellant Microthrusters

- Monopropellant, e.g. $H_2O_2(l) \xrightarrow{Catalyst} H_2O(g) + O_2(g) + 108kJ$



- Bipropellant, e.g. $N_2H_4(l) + H_2O_2(l) \longrightarrow 2H_2O(g) + N_2(g) + H_2(g) + 346.4kJ$



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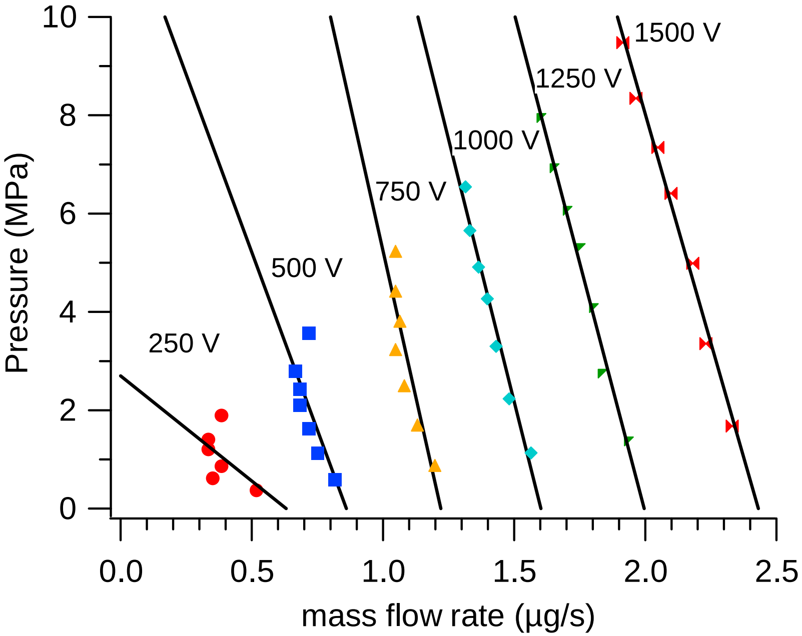
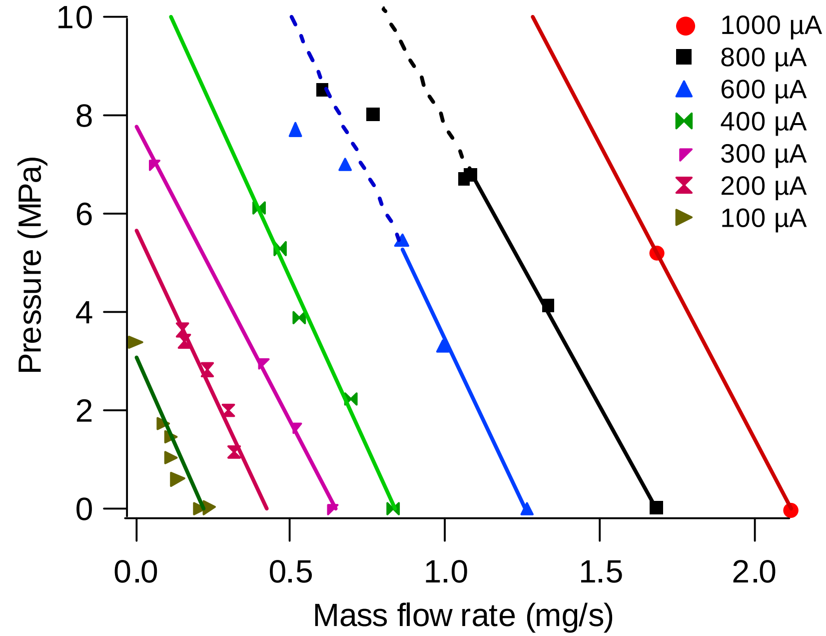
Electrokinetic Pumping of Propellants

Capillary EK pump



- **Direct pumping of N_2H_4**
  - Smallest form factor
  - 4.6 psi/volt work efficiency
  - 96 nL/min/kV performance
  - 2-3% power conversion efficiency

Sintered-monolith EK pump



- **Indirect pumping w/ hydraulic fluid**
  - Compatibility will all fuels
  - 7.0 psi/volt
  - 20 µL/min/KV
  - 2-3%

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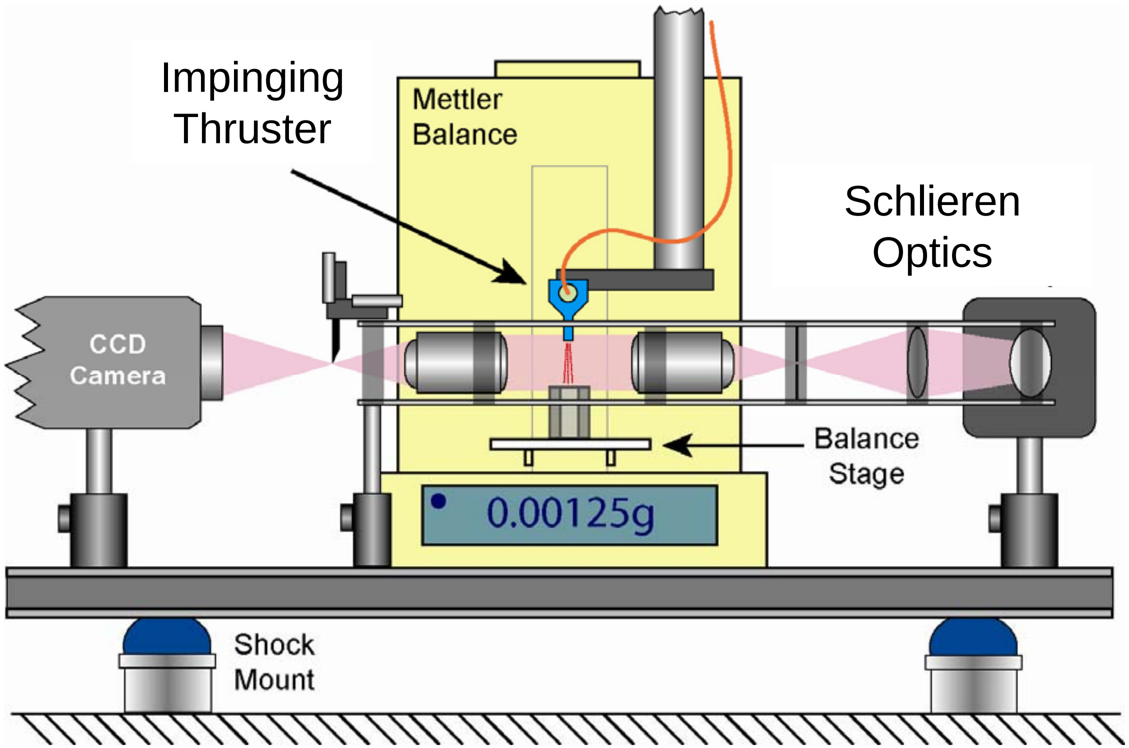
Experimental Apparatus



- Mettler-Toledo precision balance for thrust force measurement
  - 0.1 μN thrust resolution
  - Average sampling rate 8.6 Hz
- White-light Schlieren setup for in-situ thrust plume visualization

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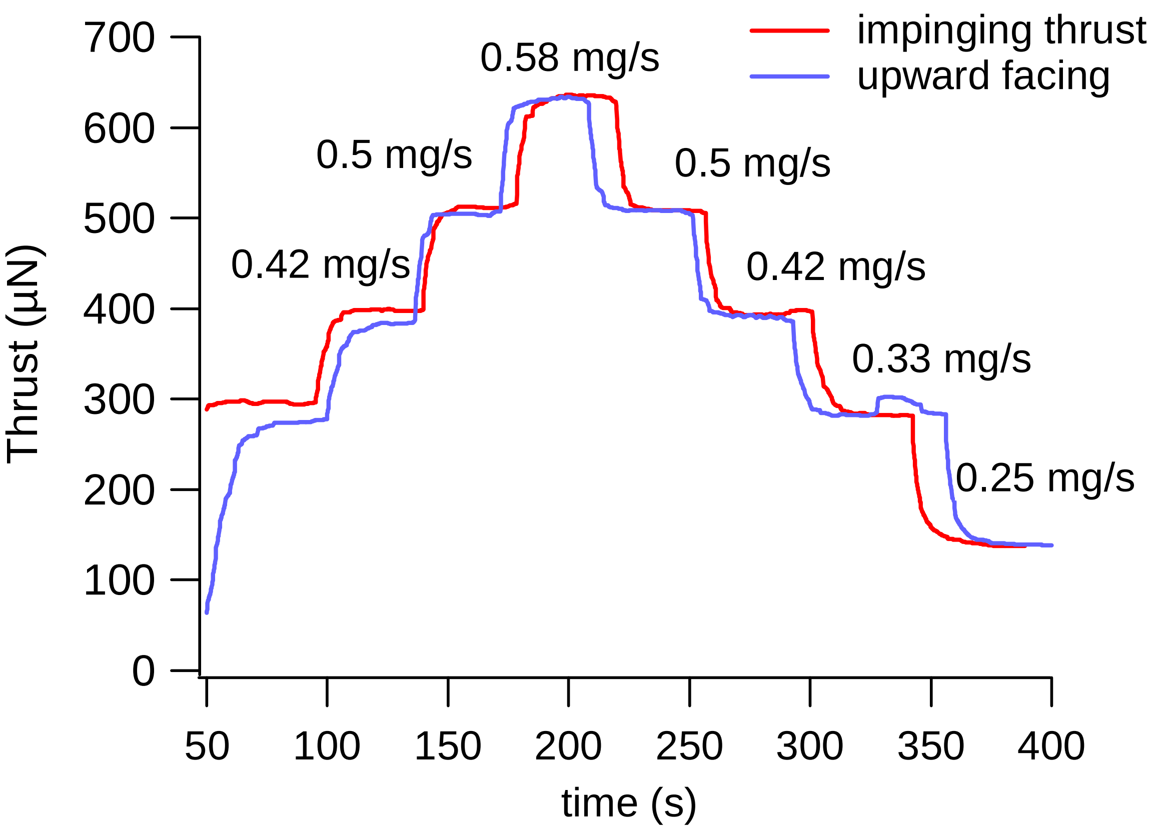
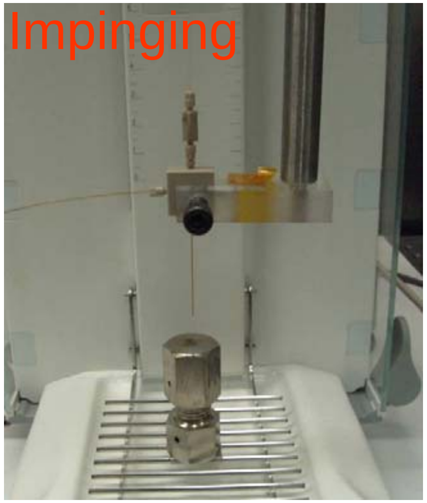
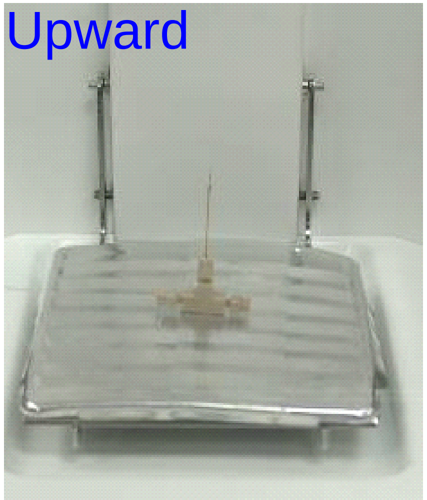
Thrust Measurement – Orientation







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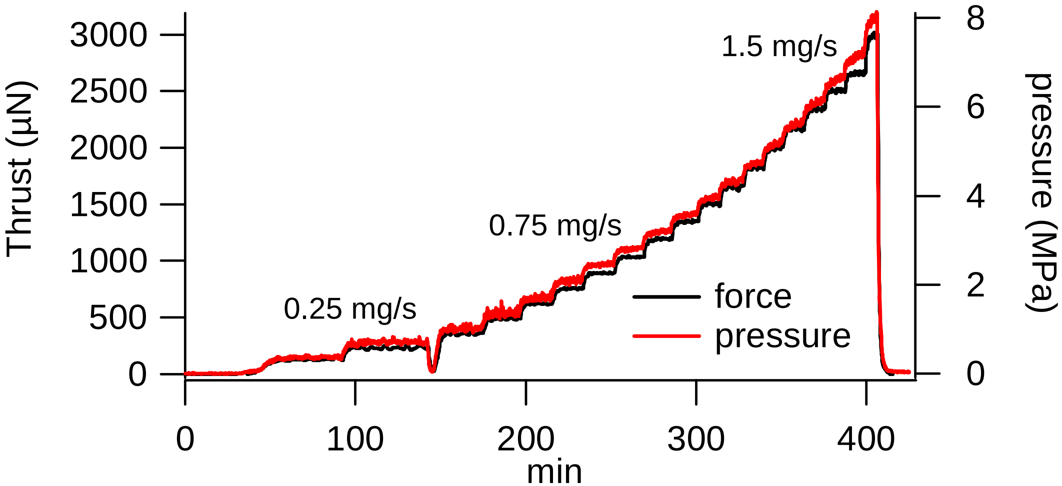
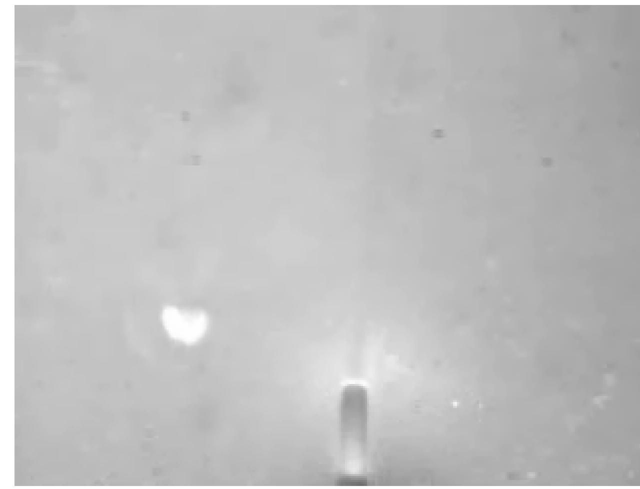
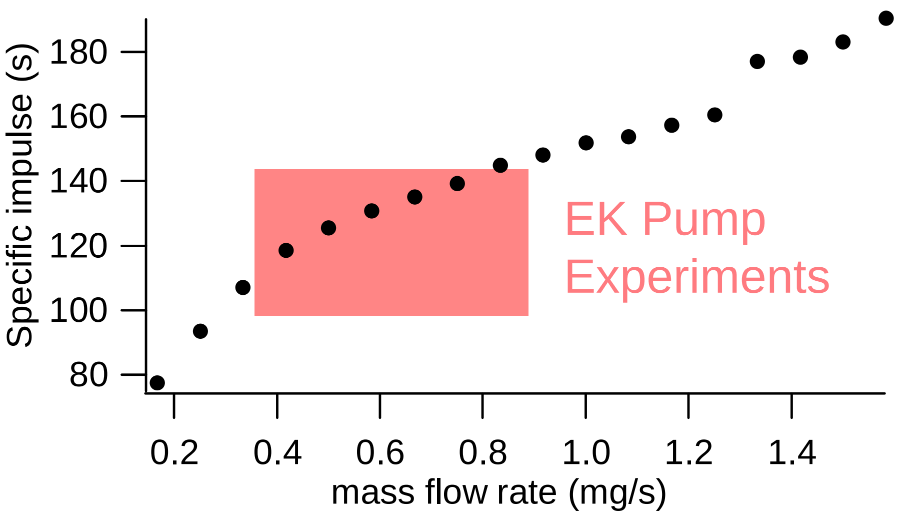
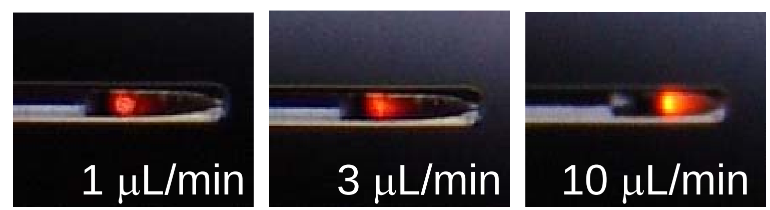
Capillary Nozzle Performance









Hydrazine monopropellant

- Catalyst pre-heating required
- Operation in subsonic regime
- Pressure drop across catalyst bed limits performance

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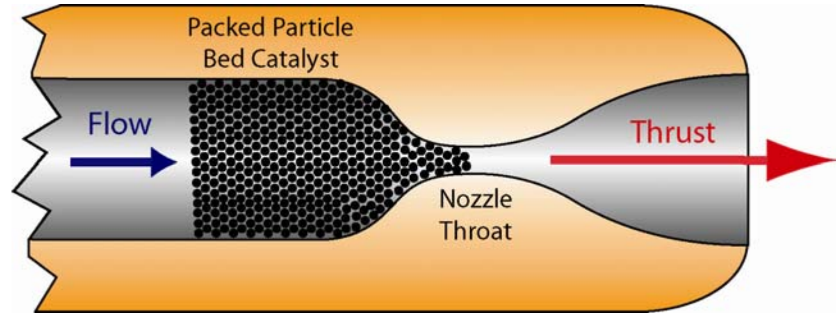
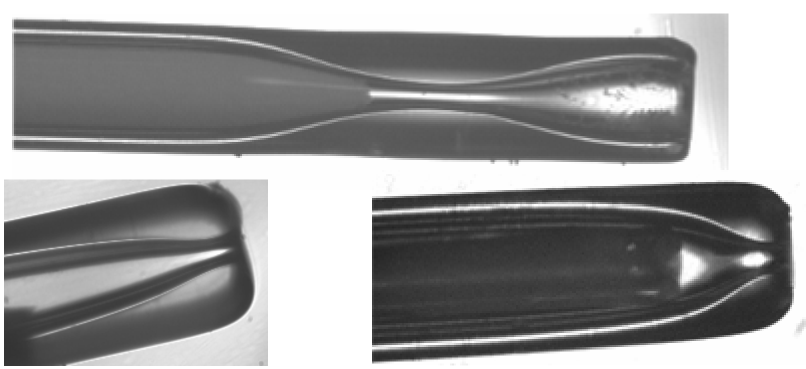
Capillary Thruster Fabrication

- Fused silica capillary nozzles
  - Plasma arc fiber-splicer used to form nozzle
  - Converging and converging-diverging nozzle geometries
  - Various throat diameters and throat / exit area ratios possible
  - Resistant to high pressures & temperatures
- Integrated catalyst
  - Silver wire / particles
  - Iridium particles
  - Porous silica particles (~10um) with iridium powder (10-50um)



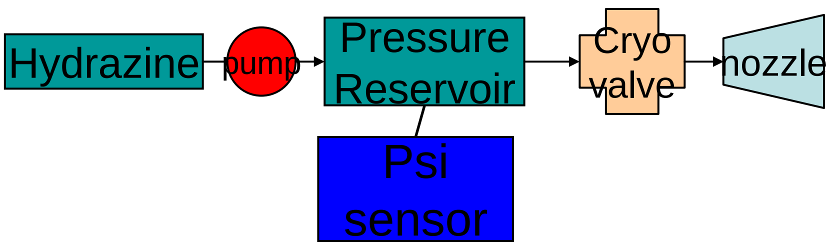
Nozzle formation – 8x actual speed



Pulsed & Continuous Thrusting

Capillary EK pump

Pulsed Mode

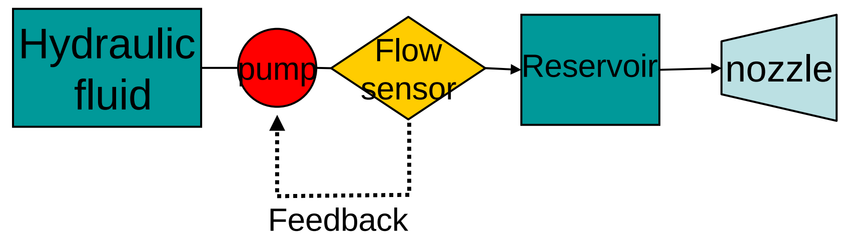


- **Discrete short impulses (<10 sec)**

  - Smaller size
  - Requires a fast, low-volume valve
  - Cryovalve to freeze the plug of fuel inline
  - Potentially most efficient

Sintered-monolith EK pump

Continuous Mode



- **Long total impulse (<11.2 min)**

  - Maximum thrust control
  - Fast reaction time
  - Constant thrust
  - Higher reliability and dependability

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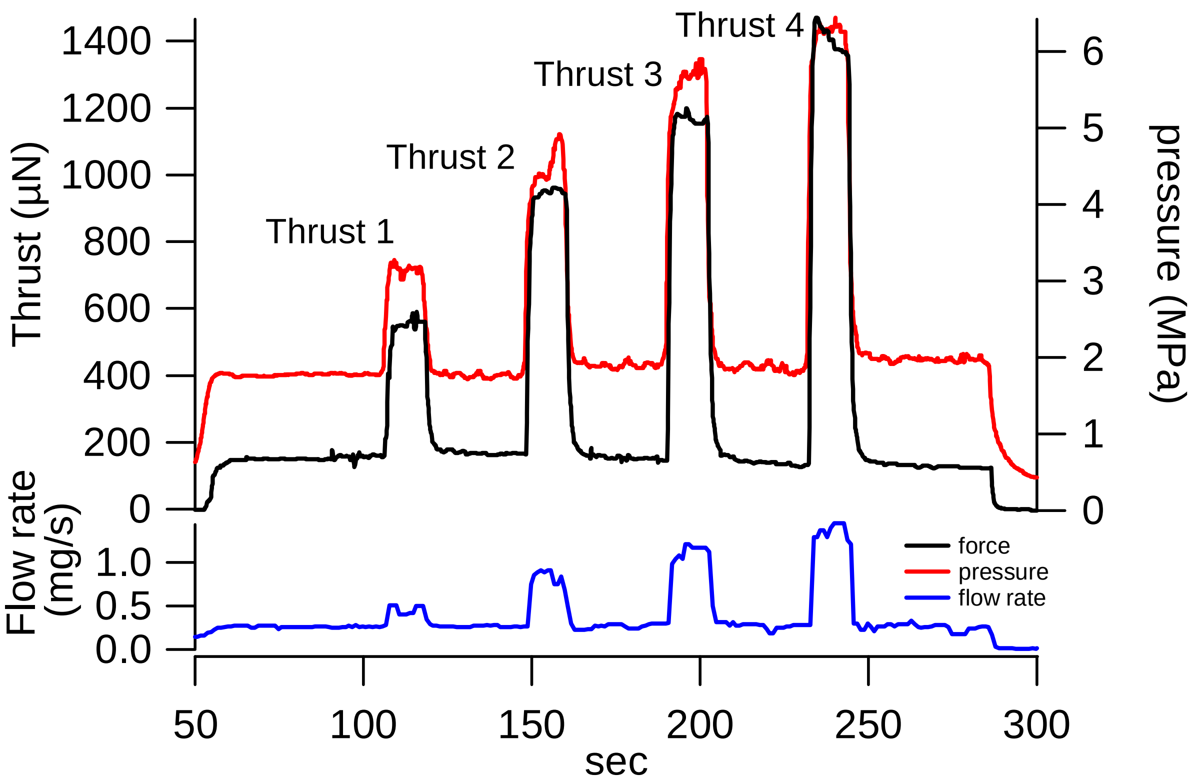
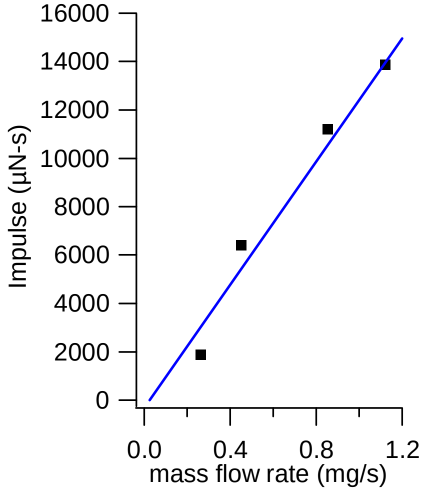
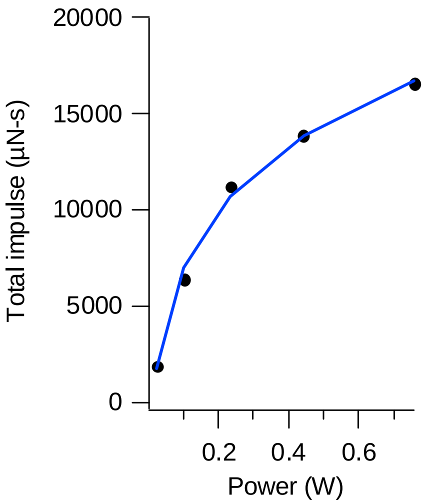
Large-Format EK Pump: Continuous Thrust Experiments







- Sintered-monolith EK pump
- Indirect pumping of hydrazine
- Closed-loop PID control based on flow rate

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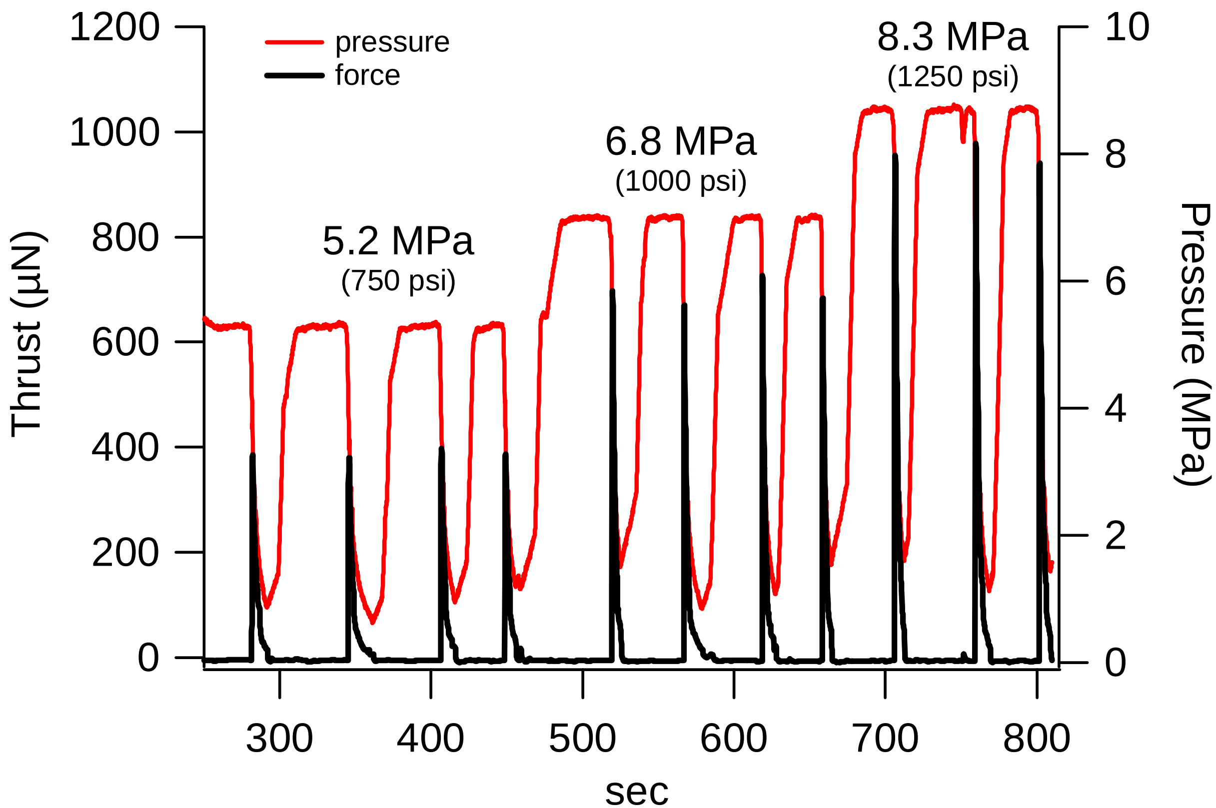
Capillary EK Pump: Pulsed Thrust Experiments



- “Cryogenic valve” creates high pressure freeze plug
- Initial pressurization against plug using syringe pump
- Capillary EK pump ramps to high pressure before release

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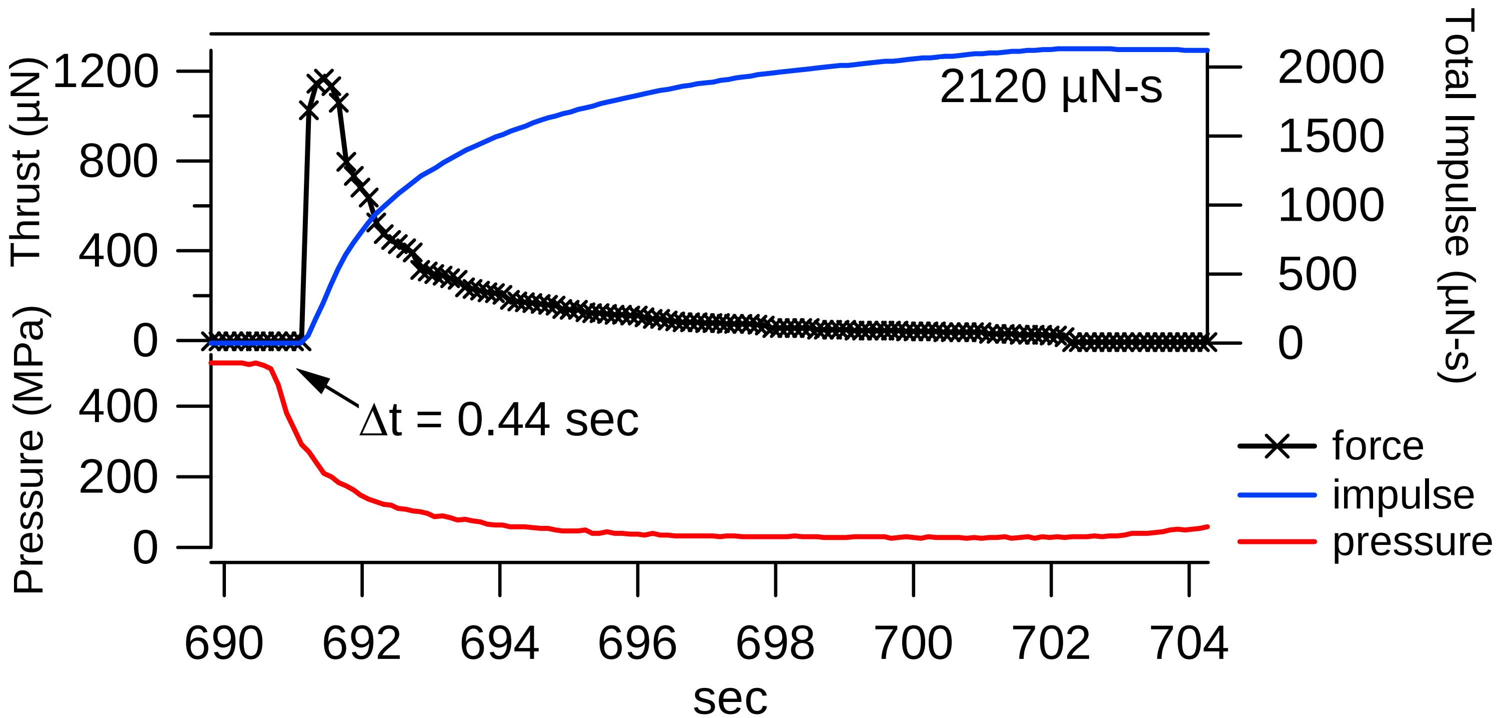
Capillary EK Pump: Pulsed Thrust Experiments



- Single thrust pulse (cryovalve release) event
- Thrust as prpellant vents through nozzle lags pressure slightly
- Impulse integrated over duration of pulse

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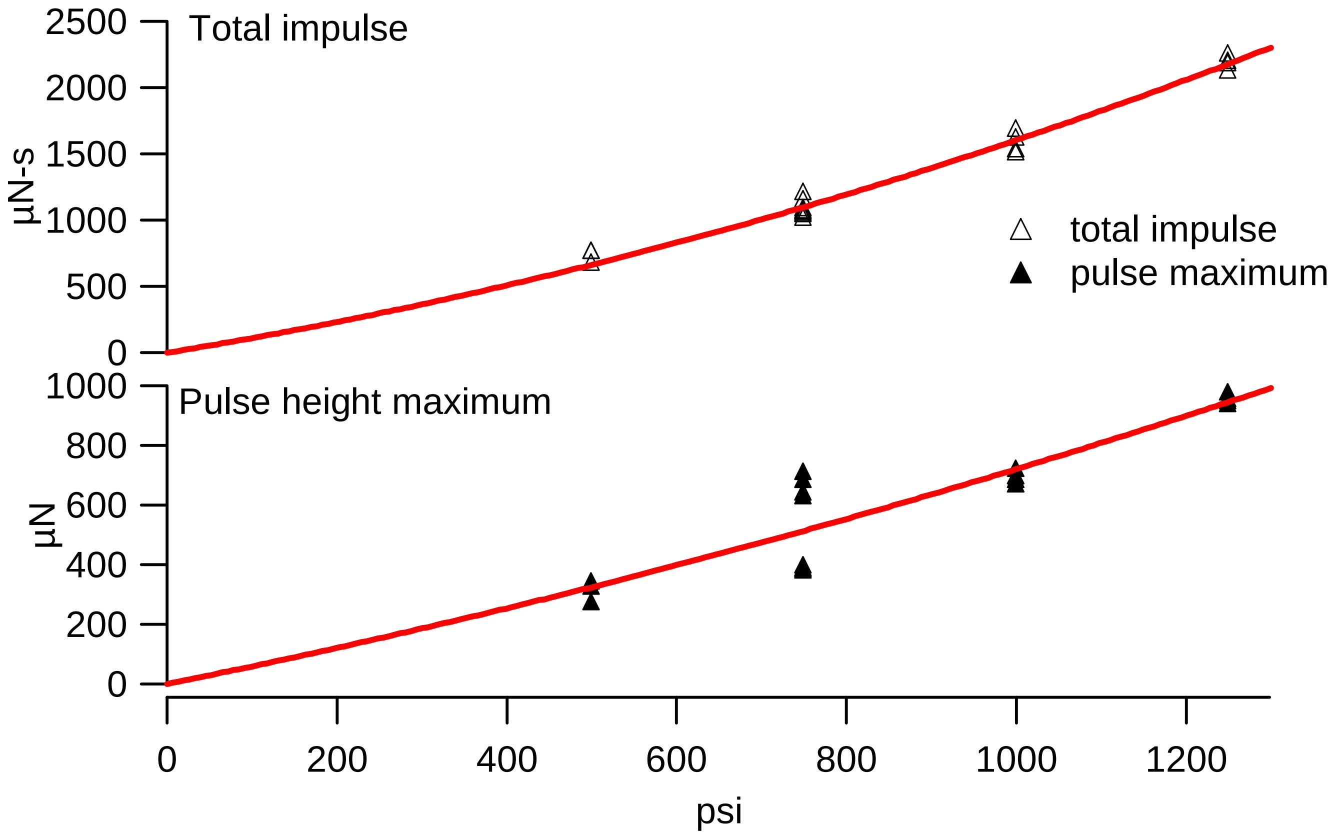
Capillary EK Pump: Pulsed Thrust Experiments



- Capillary EK pump
- Initial pressurization by syringe
- Freeze plug valve

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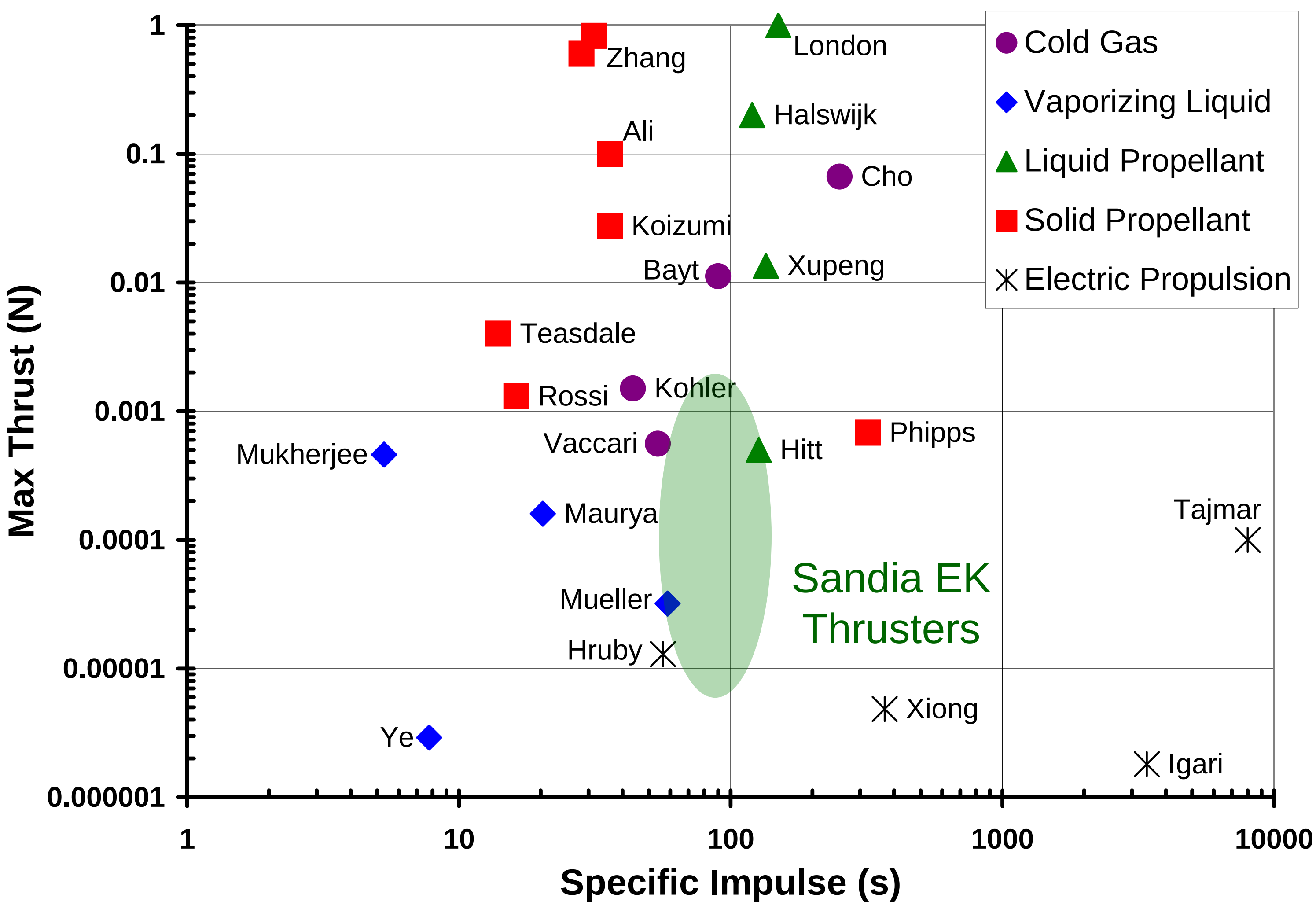
Recent Microthruster Publications

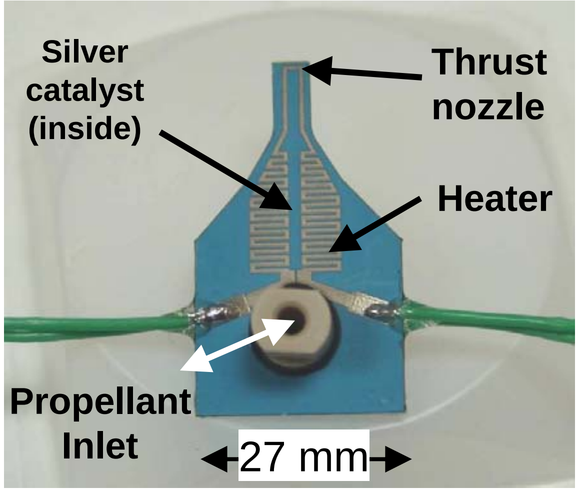


Conclusions

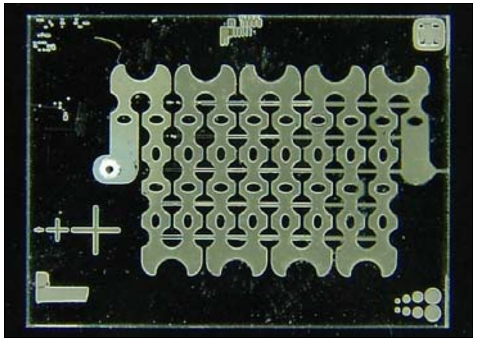
- Successfully demonstrated EK pumping of monopropellants
  - Direct / indirect pumping of hydrazine
  - Indirect pumping of hydrogen peroxide
- Fabricated & tested capillary thrusters
  - Integral particle-bed catalyst
  - Arc formed nozzle geometries
  - Hydrazine and peroxide experiments
  - Demonstrated closed loop thrust control w. EK pumping
  - Demonstrated cryo-valve pulsed thrust operation
  - Specific impulse & thrust range similar to other liquid propellant designs, though nozzles sub-optimal

Ongoing & Future Work

- Assemble integrated monopropellant propulsion system prototype
  - Estimated specifications
    - Mass: < 15 grams (not counting fuel)
    - Volume: < 20 cm^3 (not counting fuel)
    - Power: < 40 mW continuous, 120 mW at startup, 0 mW inactive
- Explore non-capillary thruster architectures
  - Low-temperature co-fired ceramic (LTCC)
  - Quartz / fused silica micromachined structures
  - Improve manufacturability & repeatability
  - Improve performance / efficiency
  - Integrate catalyst heating elements for startup
- Identify interested end users & partners from industry, academia, or government space agencies



LTCC Thruster prototype



Micromachined quartz thruster with iridium catalyst

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