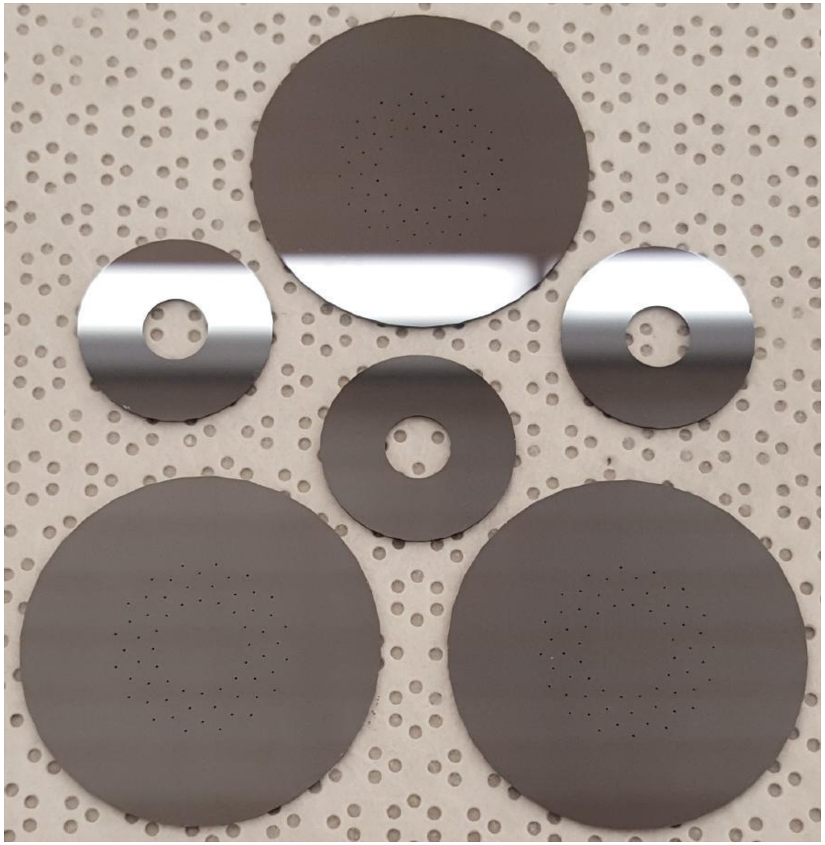
Hybrid MEMS Pneumatic Proportional Control Valve

Presenter: Nathan Hagstrom, Graduate Research Assistant
Principal Investigator: Thomas Chase
University of Minnesota

CCEFP Summit
March 8, 2018

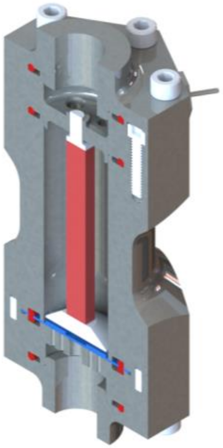
Overview

- What is a hybrid MEMS valve?
- What are alternatives to electromagnetic actuation?
- How does it work?
- How well did the prototype function?
- What are the plans for further development?

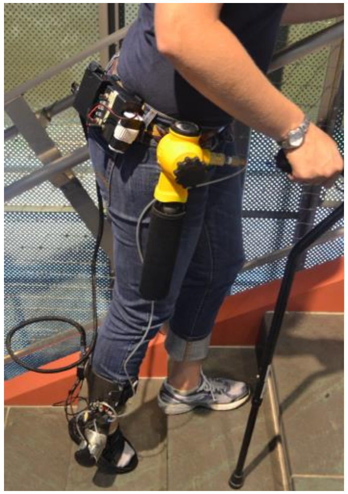


Microfabricated hybrid MEMS valve parts

Project Summary



- Use piezoelectric stack actuator to modulate flow
- Use MEMS fabrication techniques to micromachine an orifice array
- Leverage these two technologies to create an ultra efficient pneumatic proportional valve

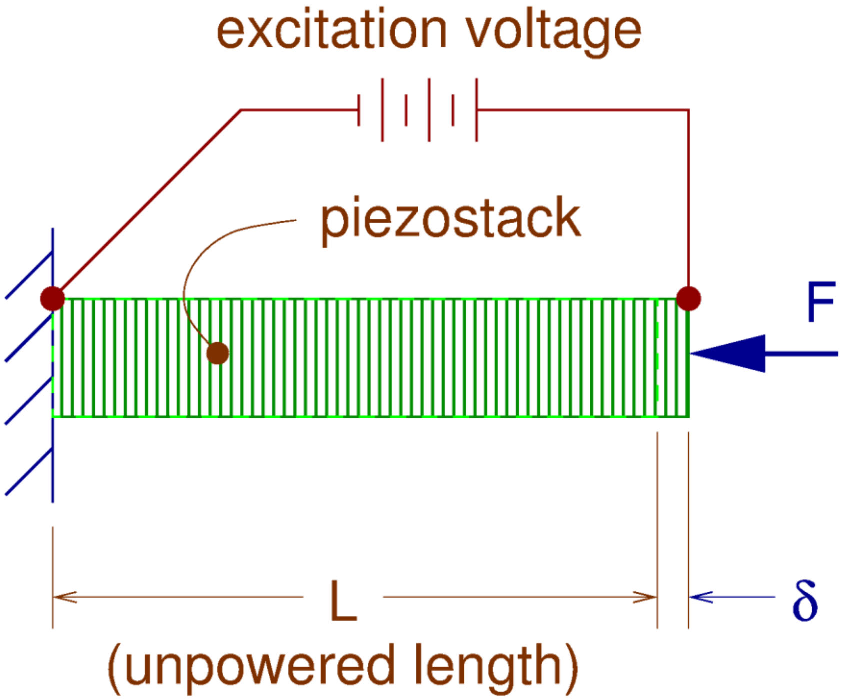


Courtesy University of Illinois
Project TB6 Team

Proposed Valve Benefits:

- Near zero power to hold at a fixed deflection
- Near zero heat generation
- Low cost
- Silent operation

Why Utilize of Piezoelectric Actuation?

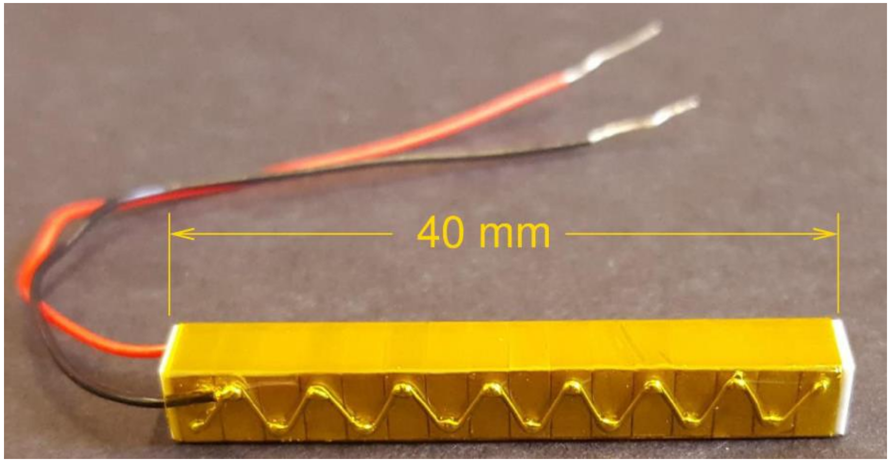


Thorlabs PK2FVP2

$L = 40\ \mathrm{mm}$

$\delta_{max} = 45\ \mu m$

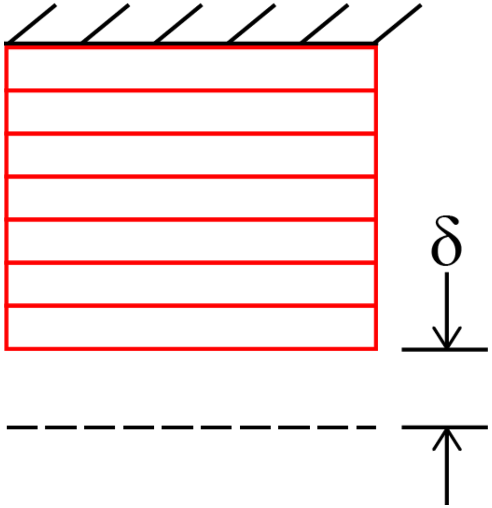
$F_{max} = 1000\ N$



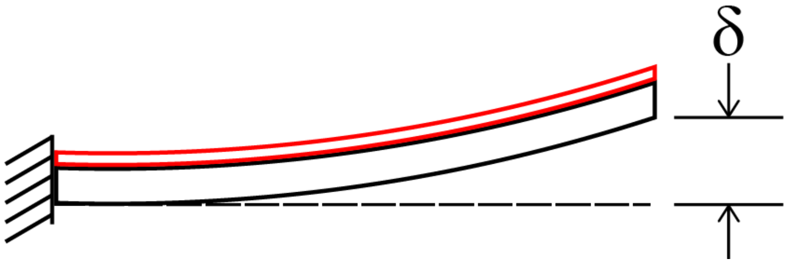
- Low static valve power consumption
- Fast response speed
- Proportional flow control at high operating pressures
- Quiet operation
- Small temperature rise at low operating frequencies
- Can be used in a magnetic field
- Compact

Modern Alternatives to Electromagnetic Actuators

Piezostack: F++ δ-



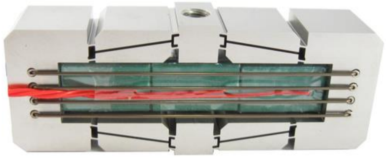
Piezobender: F- δ+



- Large displacement
- Large operating bandwidth
- Low output force
- Low power consumption

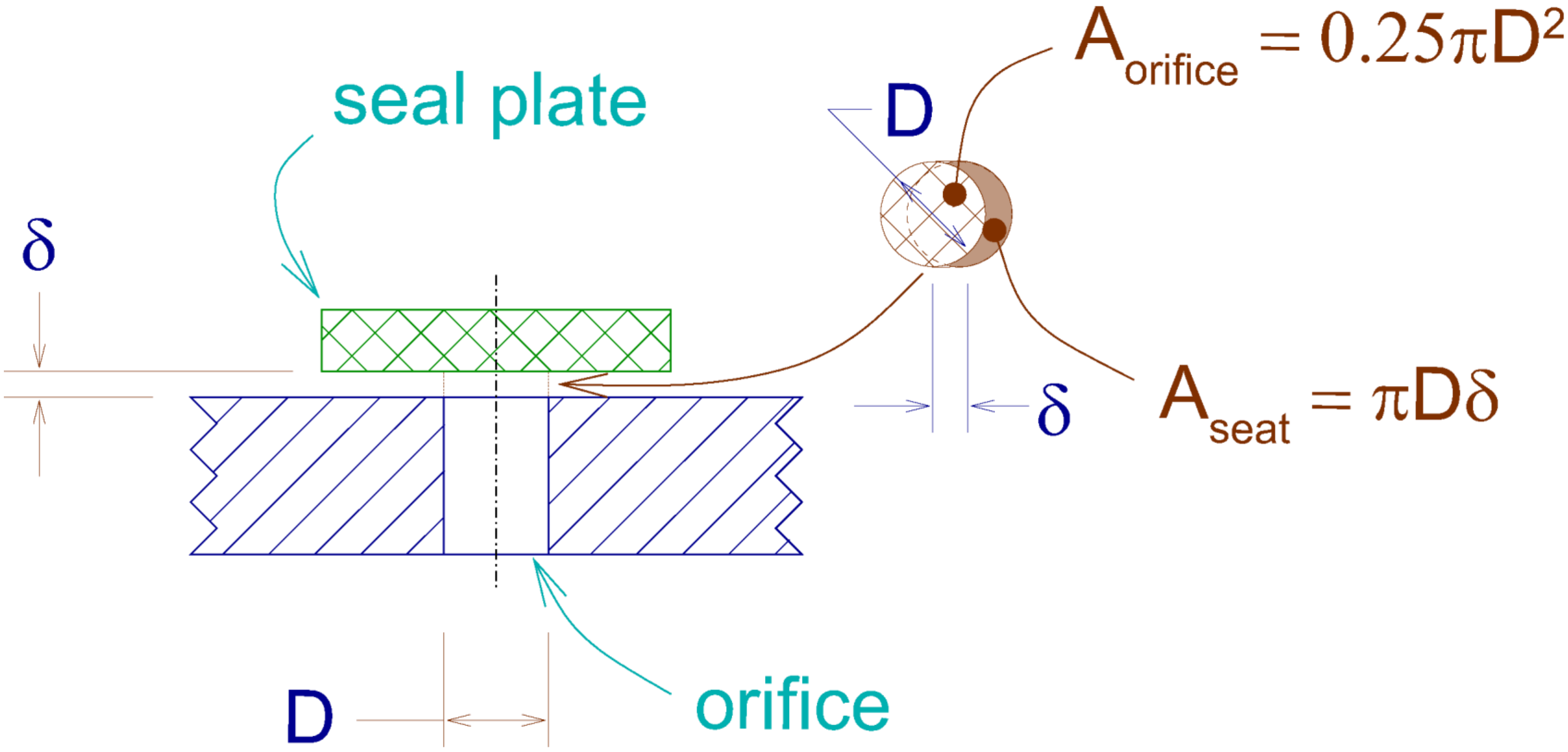
Motion Amplified Piezostack: F+ δ+

- Increased displacement
- Lower output force
- Low power consumption



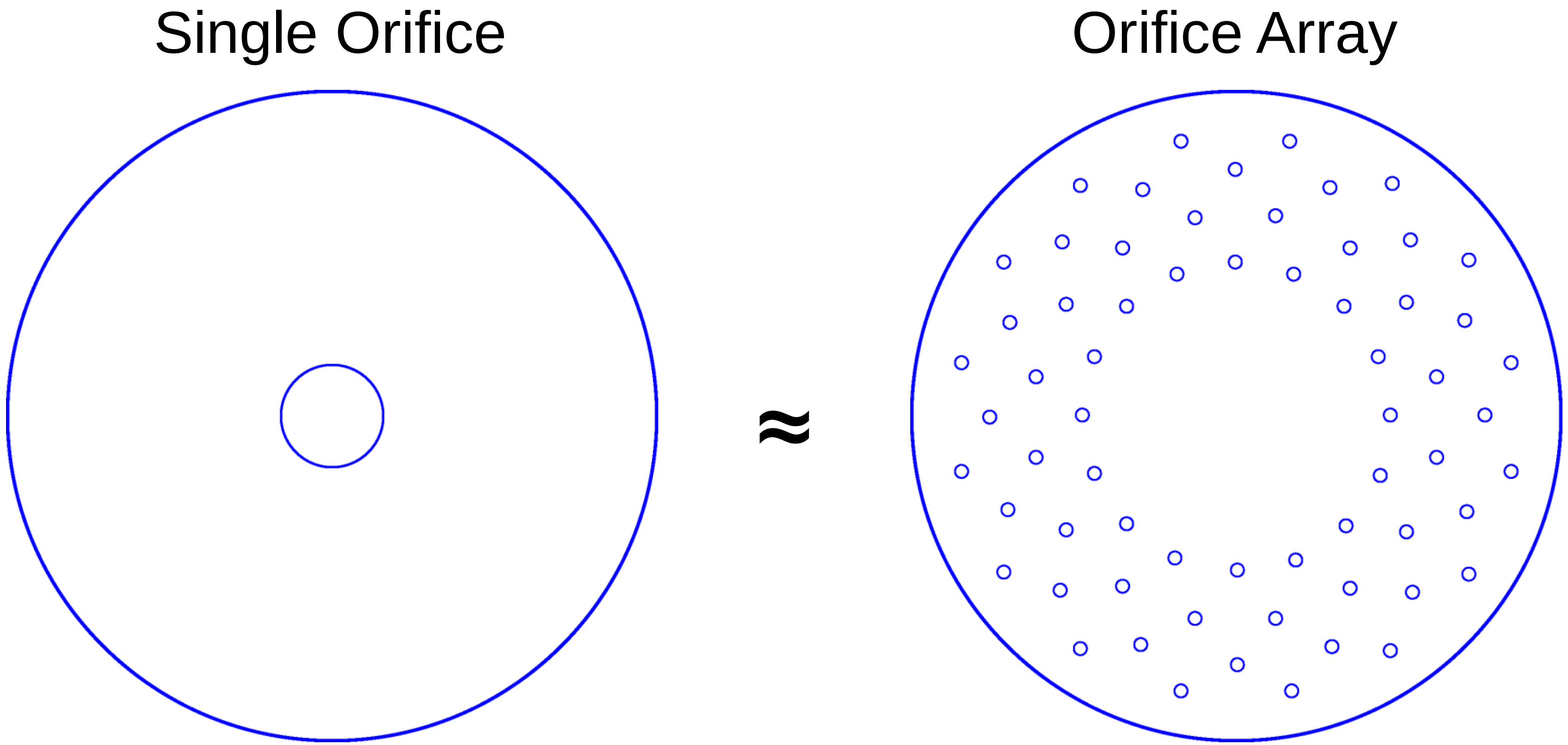
http://www.dynamic-structures.com/actuators#fpa
https://www.festo.com/cms/nl-be_be/22394.htm

Hybrid MEMS Valve Concept (1 of 2)



Full flow when $\delta \approx 0.25$ D

Hybrid MEMS Valve Concept (2 of 2)

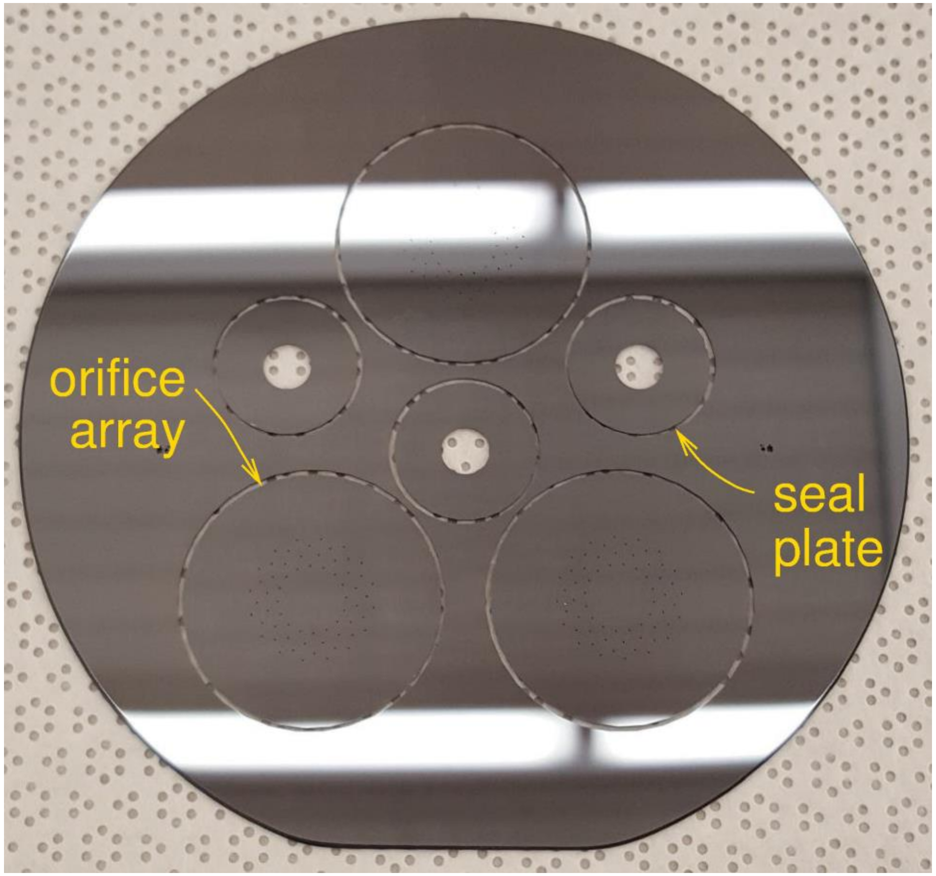


Orifice Diameter: 1.28 mm
Actuator Displacement: 320 um
Flow Area: 1.287 mm^2

Orifice Diameter: 160 um
Actuator Displacement: 40 um
Flow Area: 1.287 mm^2

Orifice array removes need for piezostack motion amplifier!

Why Fabricate Orifice Array using MEMS Fabrication Techniques?

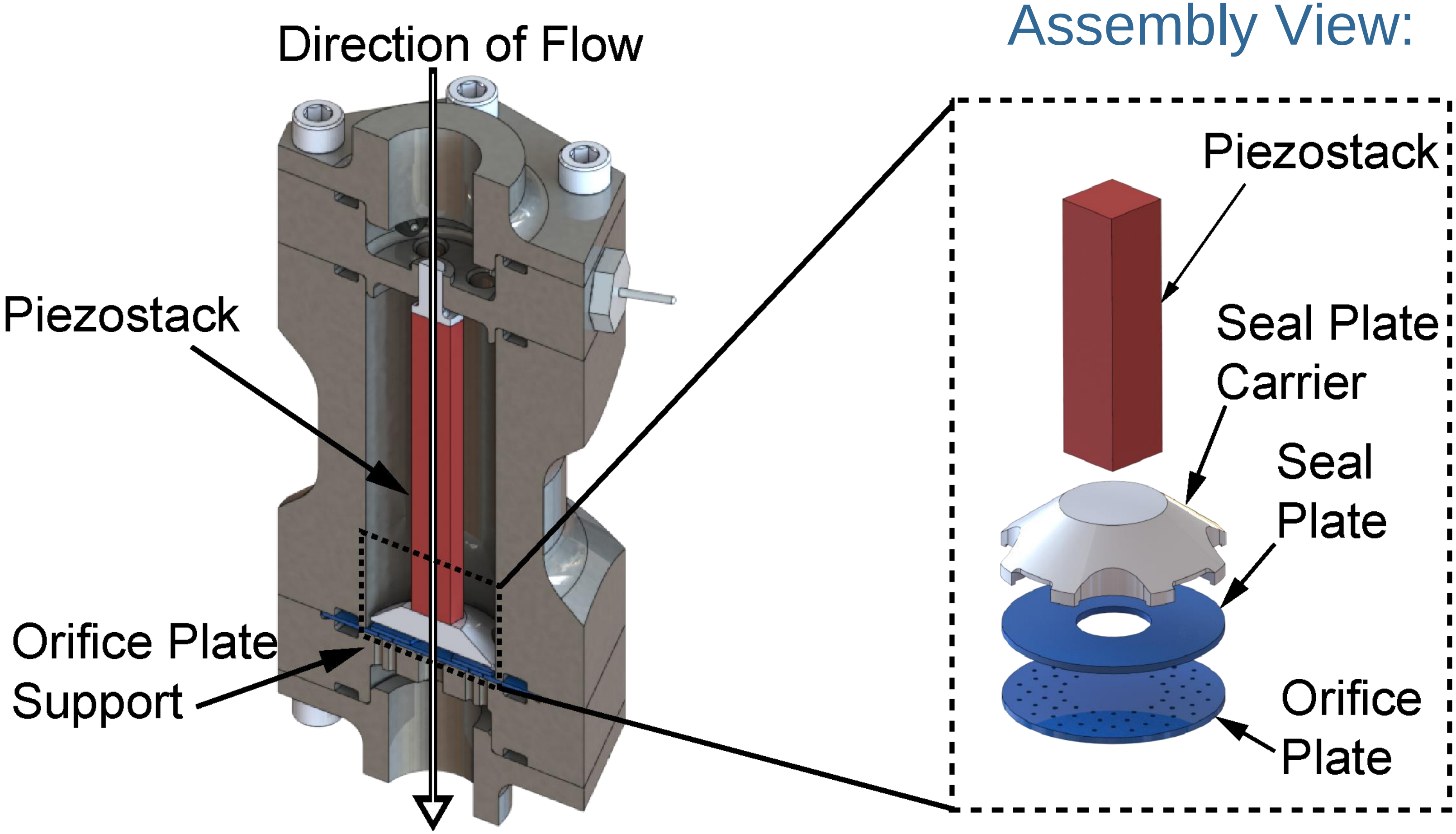


- Small orifice size in array format allow for use of piezostack actuator
- Cost effective bulk micromachining of silicon
- Silicon is stiffer and lighter than traditional materials
- Tighter tolerances on orifice features

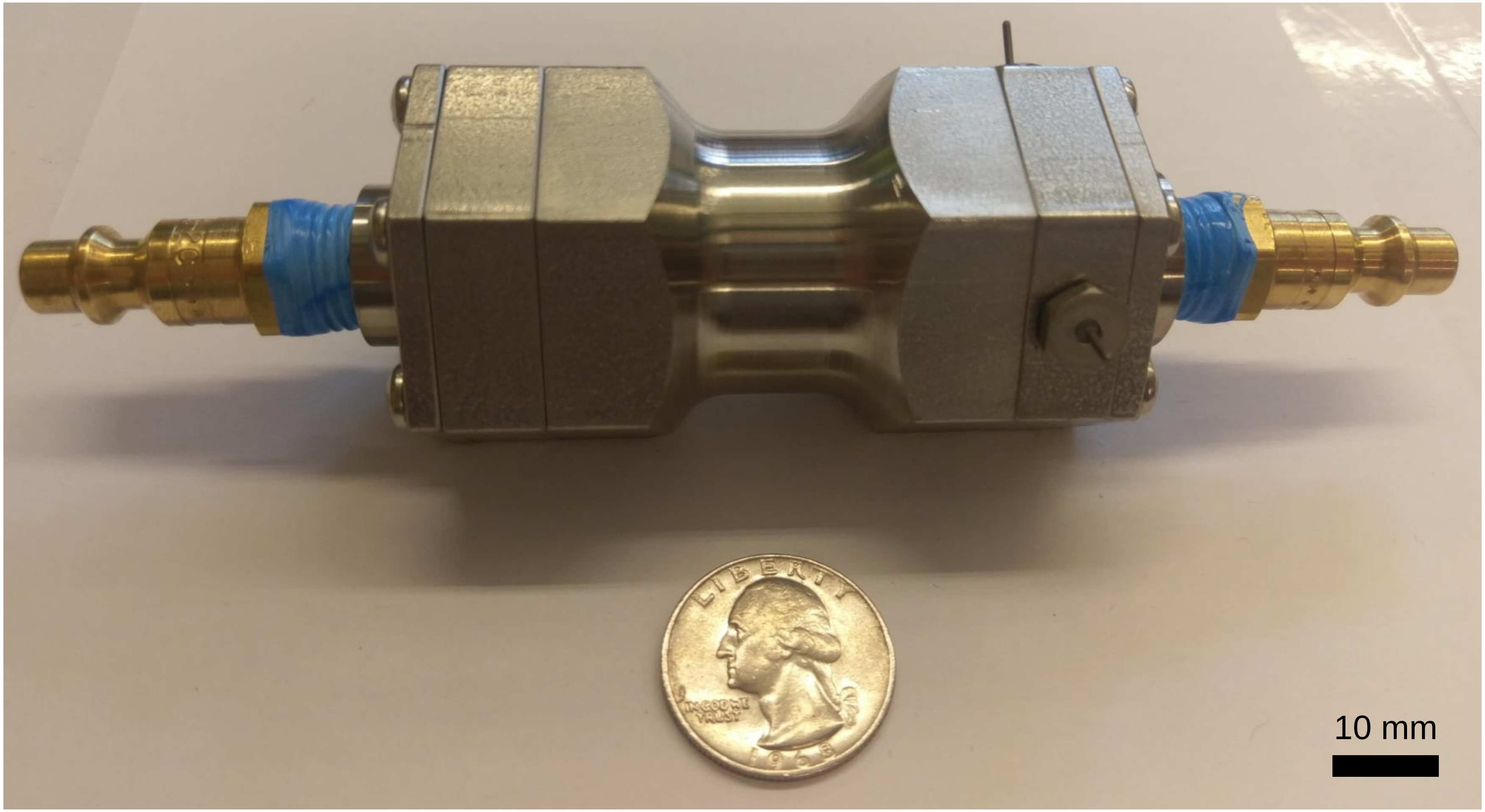
Hybrid MEMS Valve Architecture

Valve Cross-Section:

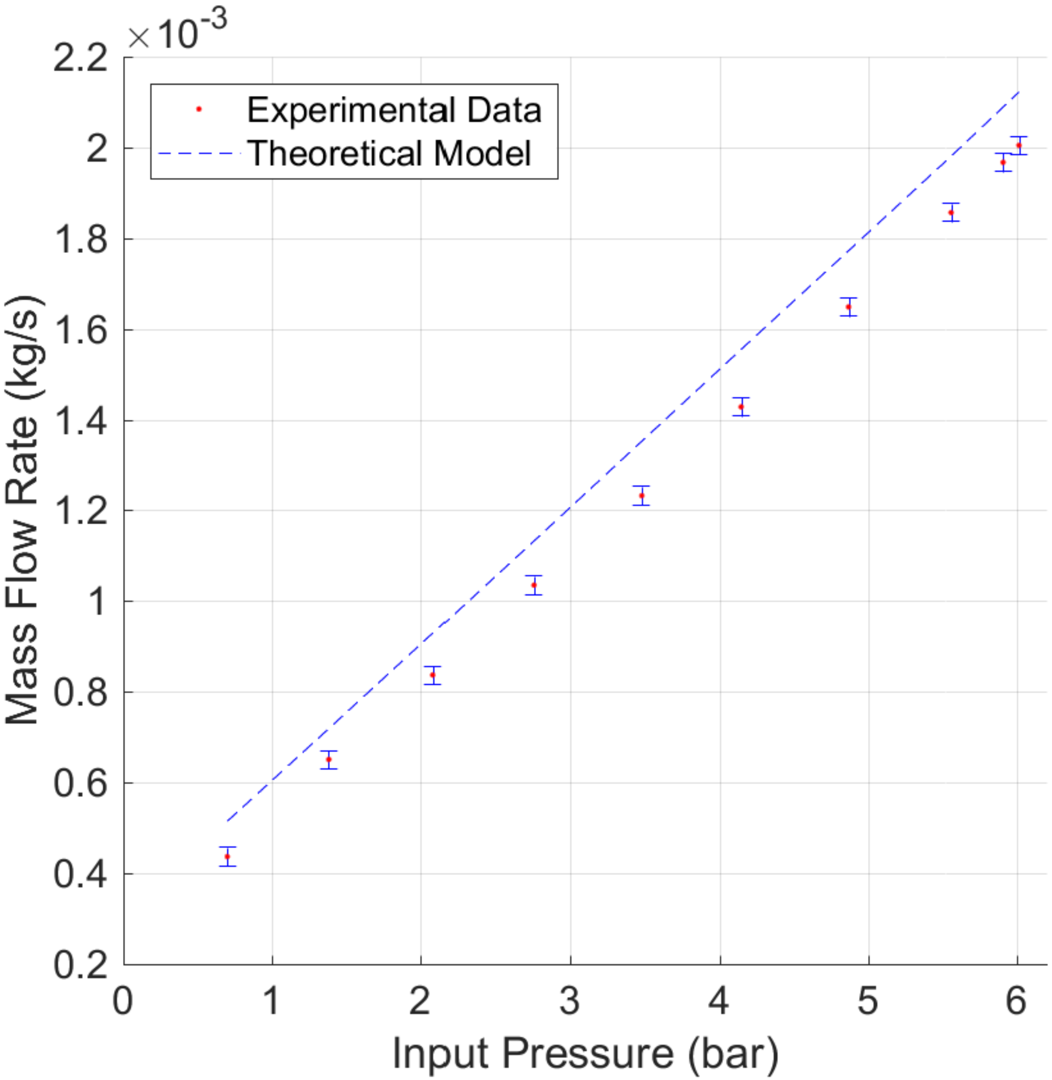
Exploded Actuator Assembly View:

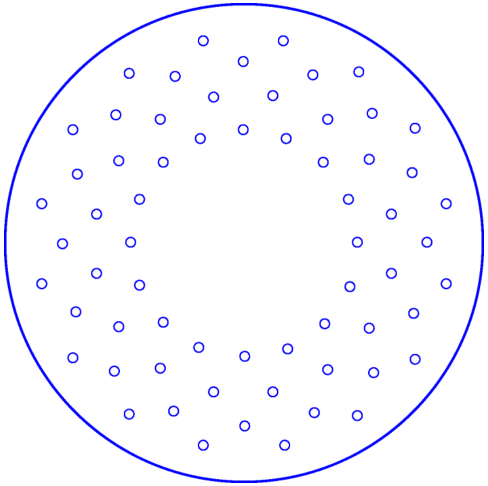


Assembled Hybrid MEMS Valve



Orifice Plate Flow Performance

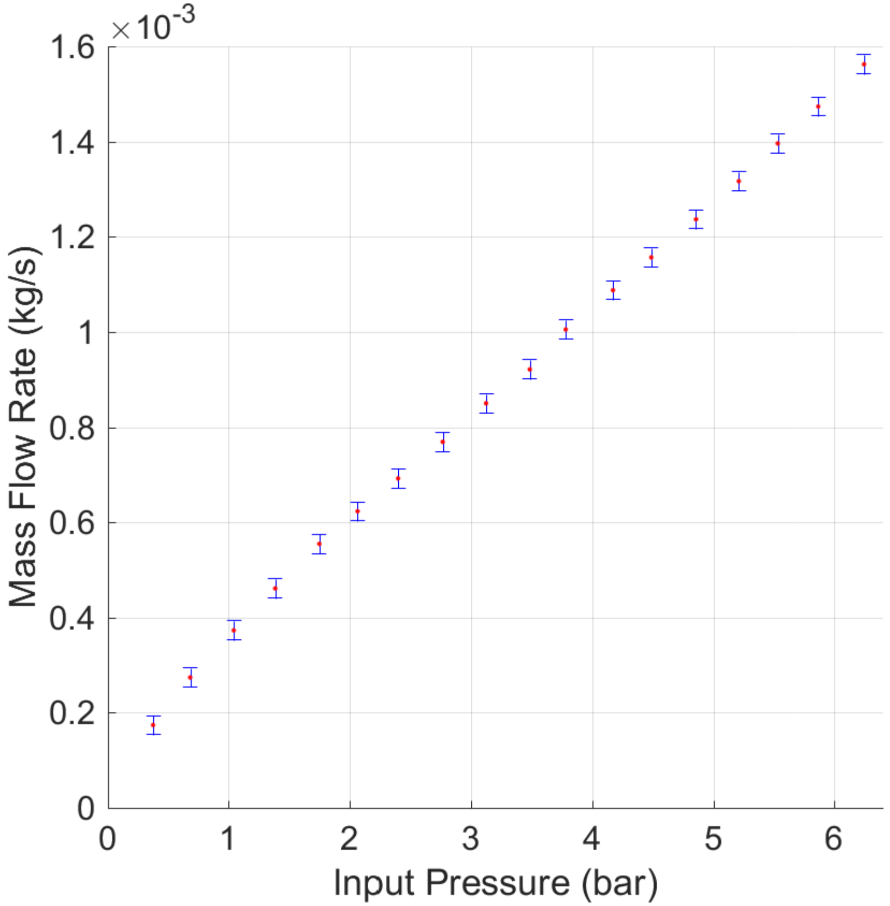




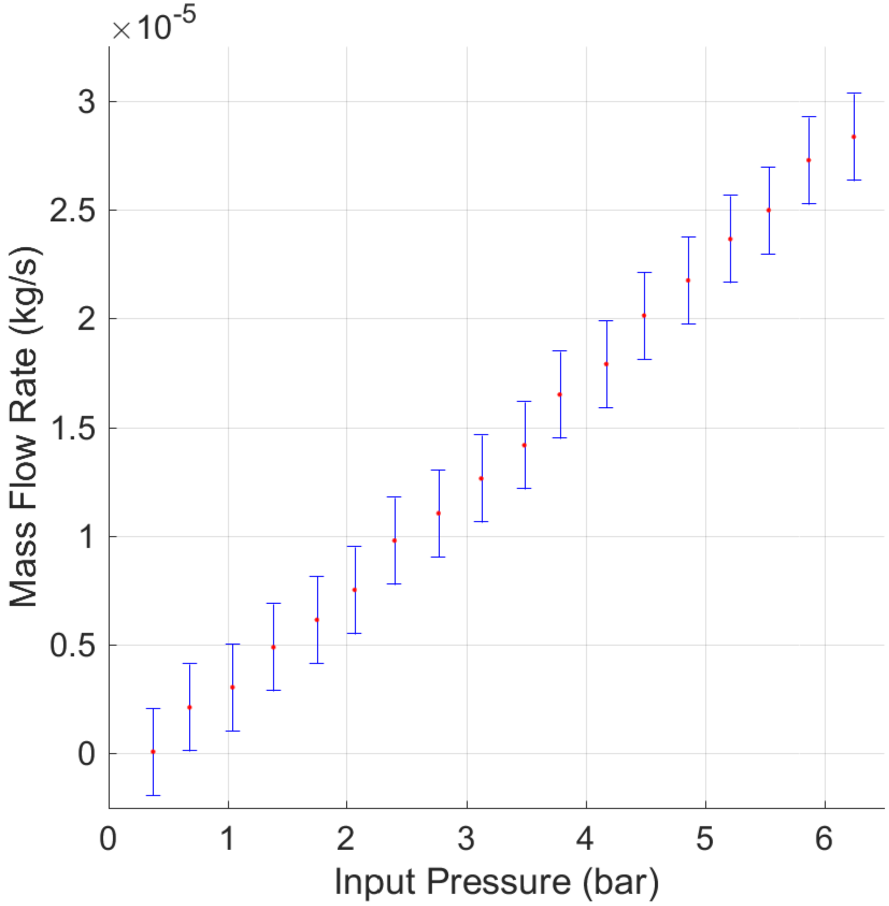
64 X 160 μm orifices

$C_D = 0.89$

Maximum v. Minimum Flow (6.205 bar)

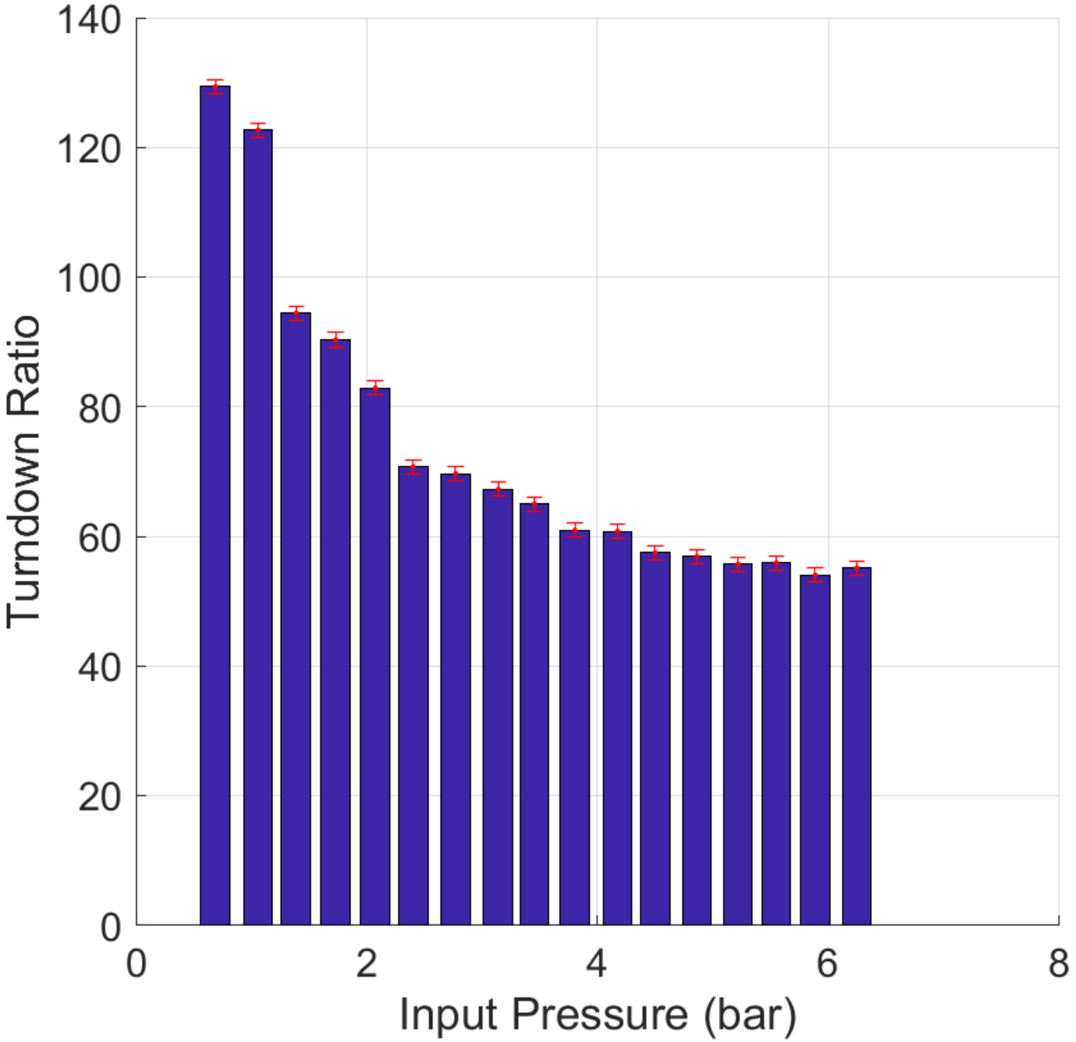


Maximum Flow: 0V Applied

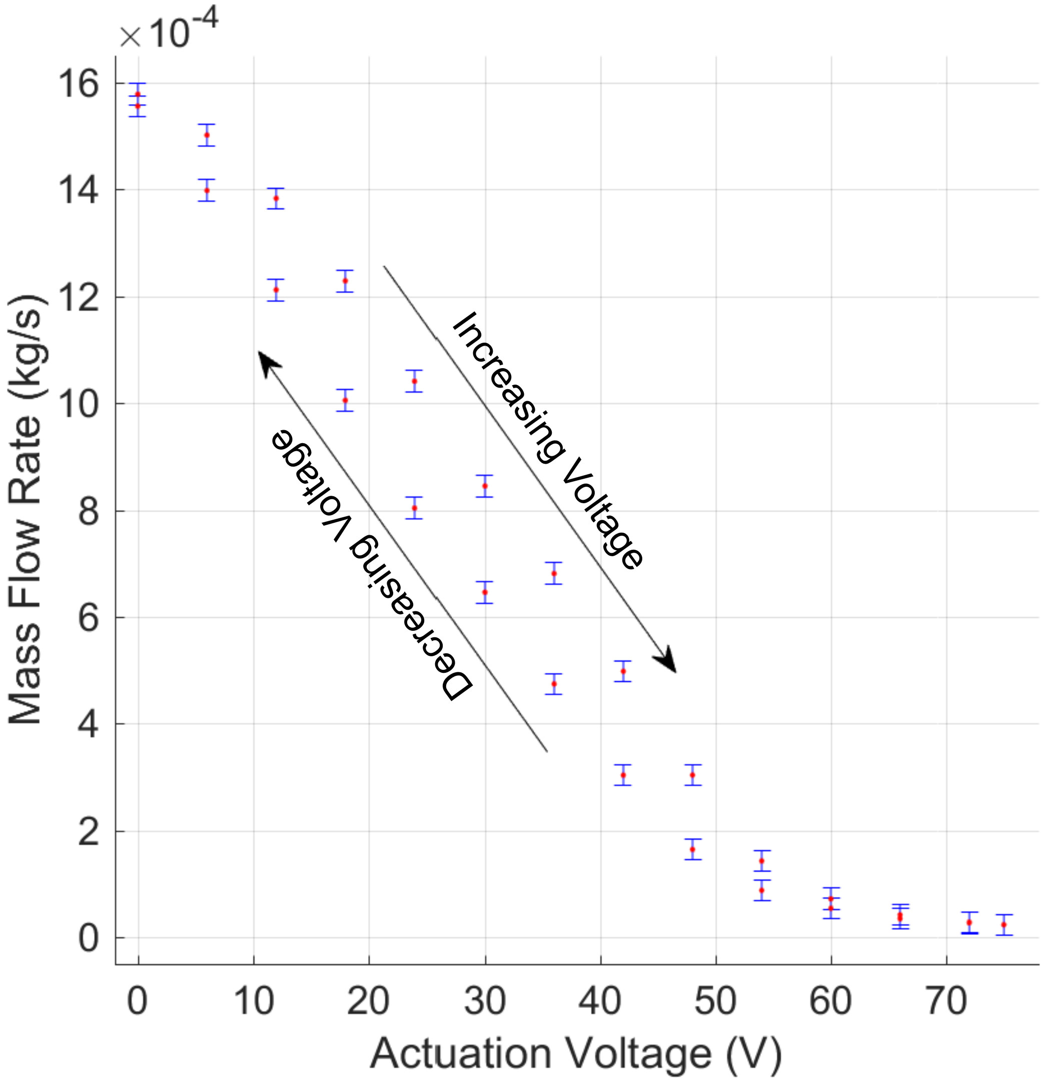


Leakage: 75V Applied

Valve Turndown Ratio



Proportional Flow Performance



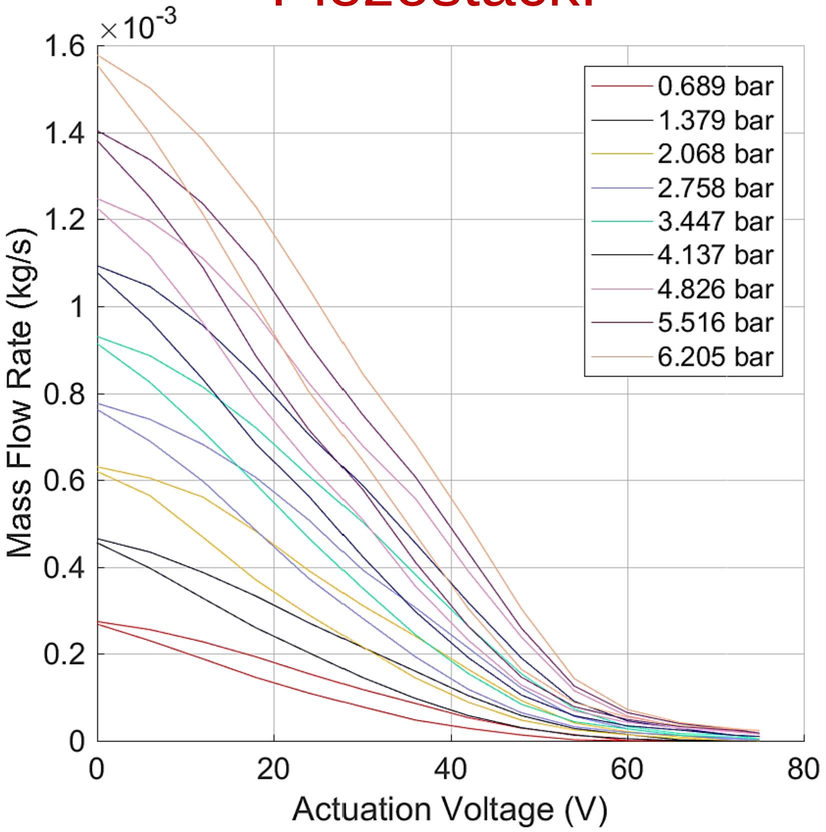
- Hysteresis characteristic of open loop voltage input
- Operating Pressure: 6.205 bar

Mass Flow Rate Eqn:

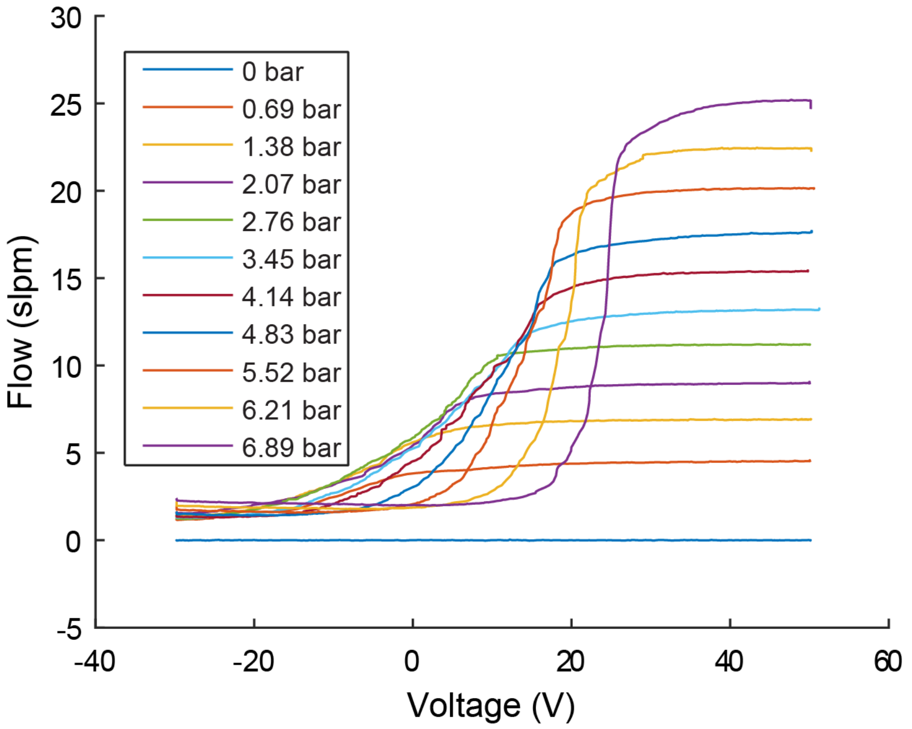
$$\dot{m} = C_D \pi D \delta P^* \sqrt{\frac{\gamma}{RT^*}}$$

Piezostack v. Piezobender Proportional Flow Performance

Piezostack:



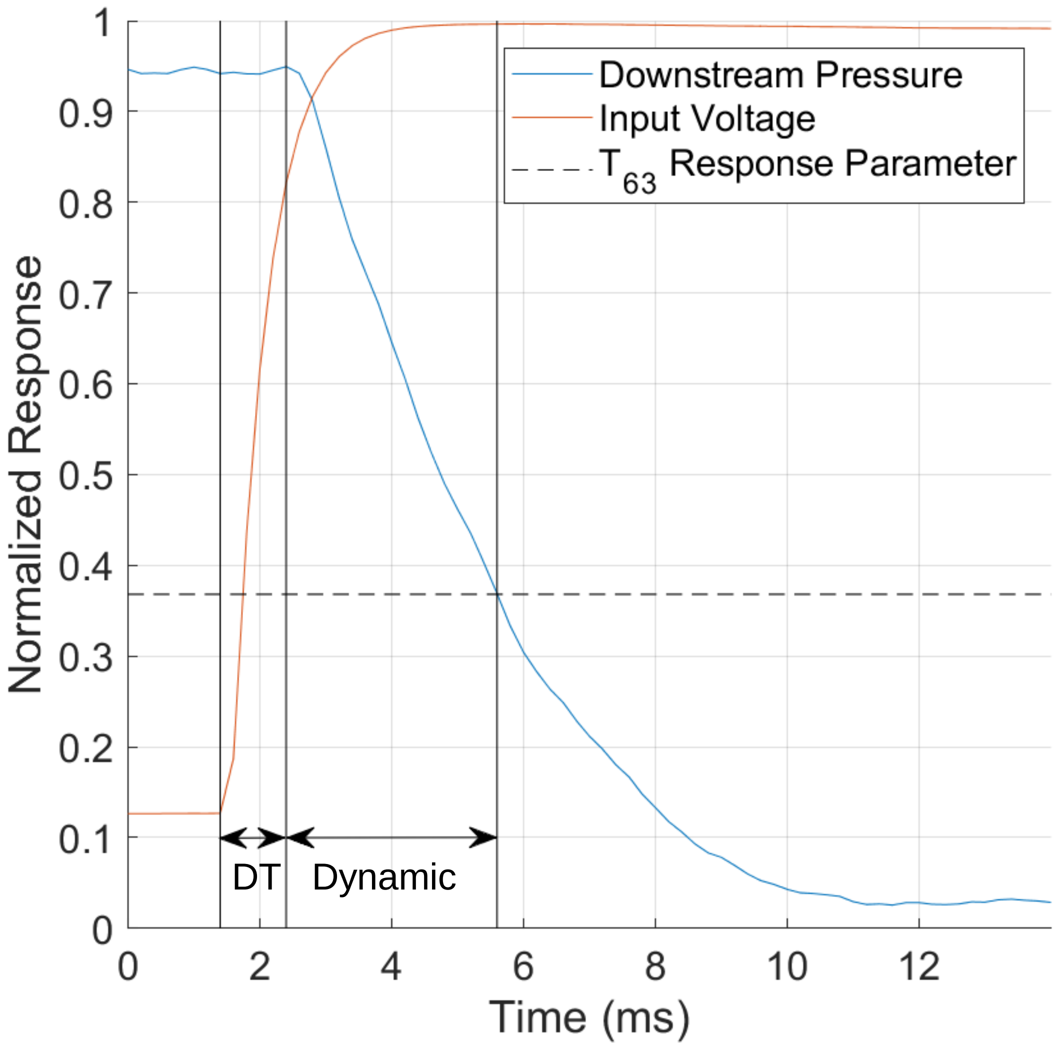
Piezobender:



Piezostack Proportionality >> Piezobender Proportionality

Piezostack proportionality is independent of pressure

Valve Transient Response



DT: valve dead time

Dynamic: valve dynamic time

DT = 1 ms

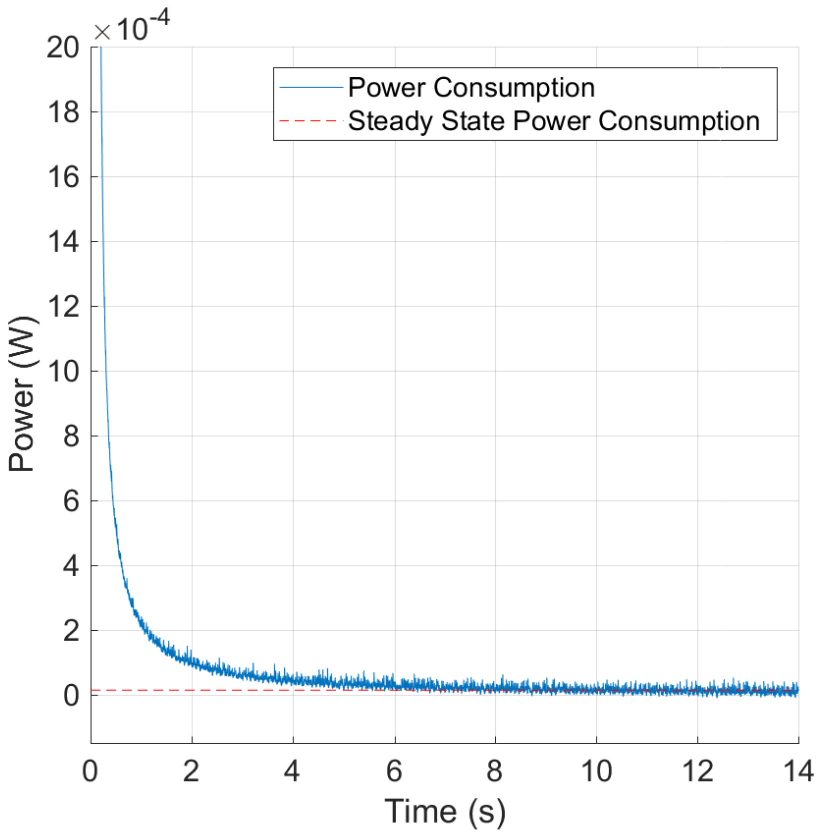
Dynamic = 3.2 ms

Response Time = 4.2 ms

Pressure dynamics of test stand artificially increased measured response time

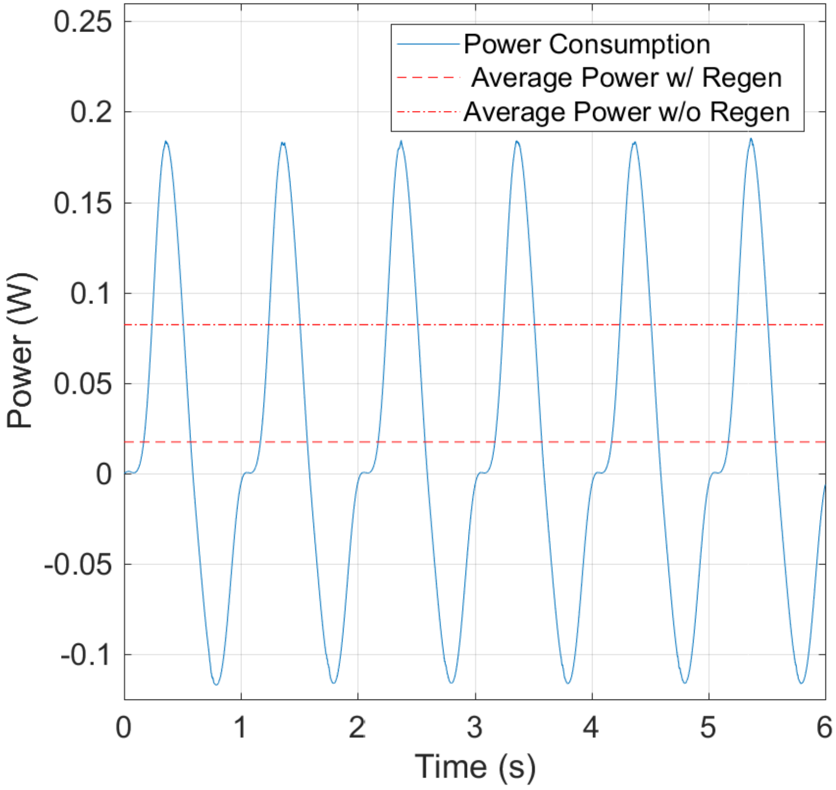
Valve Power Draw

Static Power Consumption:



Steady State Power: 13.1 μW

Dynamic Power Consumption:



Peak Power: 0.18W
Average Power: 15.7, 82.2 mW

Competing Miniature Proportional Valves

Manufacturer	Actuation Method	Max Pressure (bar)	Flow Rate* (SLPM)	Avg Power (W)	Response Time (ms)
Commercial Valve 1	Electromagenetic	10.3	178.1	3.6	2.4
Commercial Valve 2	Electromagenetic	3.5	57.9	--	--
Commercial Valve 3	Electromagenetic	6.9	201.6	2.2	10
Commercial Valve 4	Electromagenetic	6.9	10.3	1.9	--
Commercial Valve 5	Electromagenetic	6.9	54.8	6.0	< 20
Commercial Valve 6**	Piezobender	6.0	--	1.0E-3	15
Commercial Valve 7***	Amplified Piezostack	6.9	230.1	0.6	< 20
Hybrid MEMS Valve	Piezostack	6.9****	47.2	1.31E-5	4

** Flow rate a 6 to 5 bar pressure difference*

*** Macro-scale piezoelectric bender actuator*

**** Macro-scale piezoelectric stack actuator with motion amplifier*

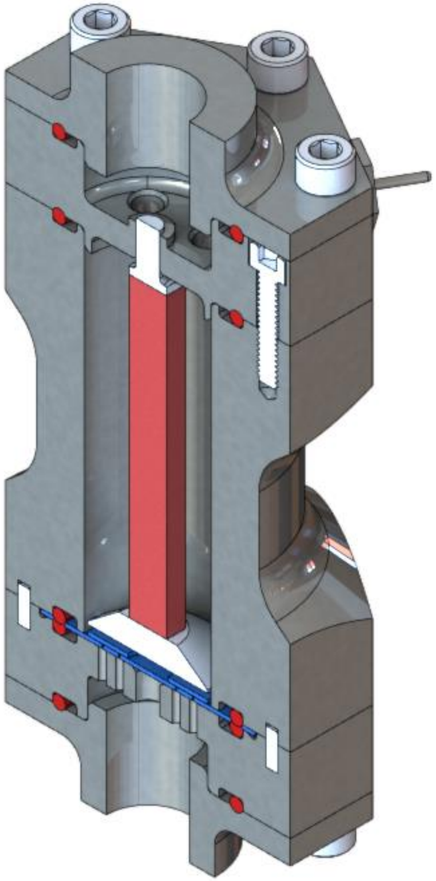
**** Limited by in house air supply

Conclusion

- 55:1 or better turndown ratio achieved across all operating pressures on concept demonstration prototype
  - Will be further improved
- Proportional but non-linear flow control
  - Will be improved with feedback control system
- 4 ms response time at 6.205 bar input pressure
  - Biased by test chamber pressure dynamics
- 13.1 µW steady state and 0.18W peak dynamic power consumption

The efficiency, compactness and performance of hybrid MEMS valves hold the potential to revolutionize pneumatic valve technology

Questions?



Valve Benefits:

- Near zero power to hold at a fixed deflection
- Proportional control
- Fast response time
- Near zero heat generation
- Low cost
- Silent operation
- Non – magnetic