Nanoscale Fluidics

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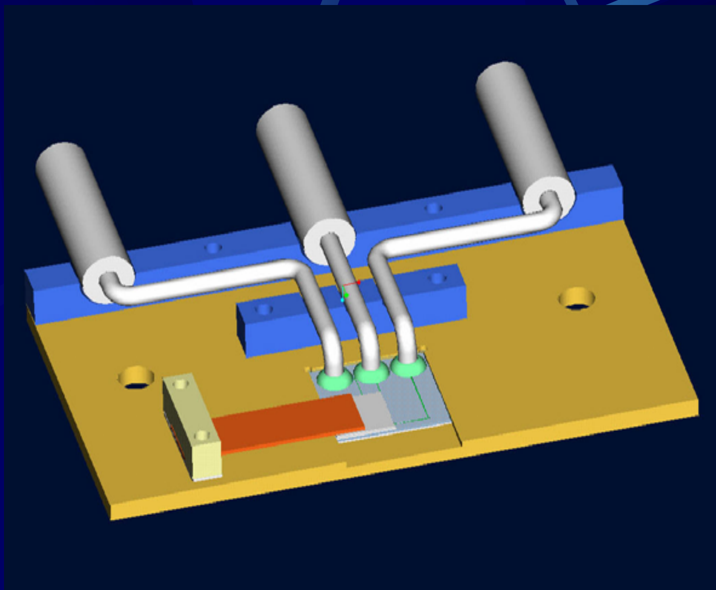
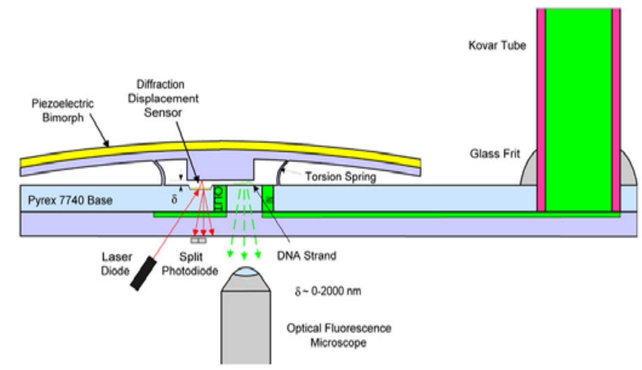
The Nanogate





Above: Schematic Cross-Section of Nanogate.

Left: Solid model of Packaged Nanogate.

- The Nanogate is micro-mechanical device that is designed to control a nanometer sized gap.
- Precise control of the gate opening is accomplished by deflecting a cantilevered plate that is anchored by a torsion spring, as shown in Figure 1.

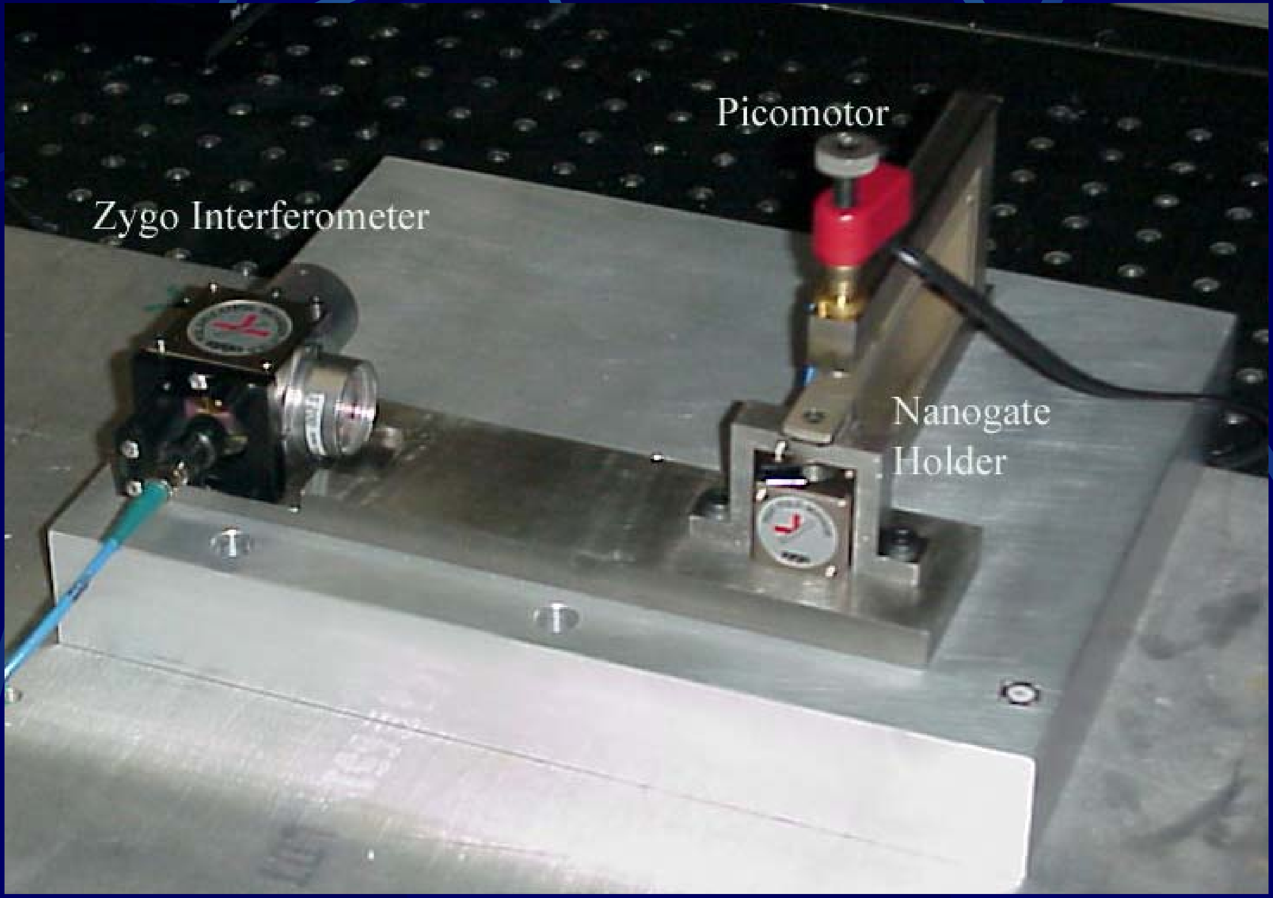
Figure 1: Schematic of the Nanogate Instrumentation

- The opening is adjustable on a sub-nanometer scale using a piezoelectric actuator.
- The ability to control flow channels at nanometer length scales enables sensing and filtration of large molecules such as proteins and DNA.
- We (H. Ma and J. White) built instrumentation for the nanogate to precisely measure and control the gate opening, to eventually use it to manipulate the flow of molecules.

Experimental Issues

- Vibration
- Thermal Drift
- Displacement measurement (alignment)
- Repeatability and reliability

Nanogate Instrumentation



Components:
- Optics bench
- Mount
- Actuation flexure
- Picomotor
- Zygo
- Syringe pump
- Computer
- Software
- Fluid Connections: not yet!

Figure 2: A picture of the nanogate instrumentation

Nanogate Mount

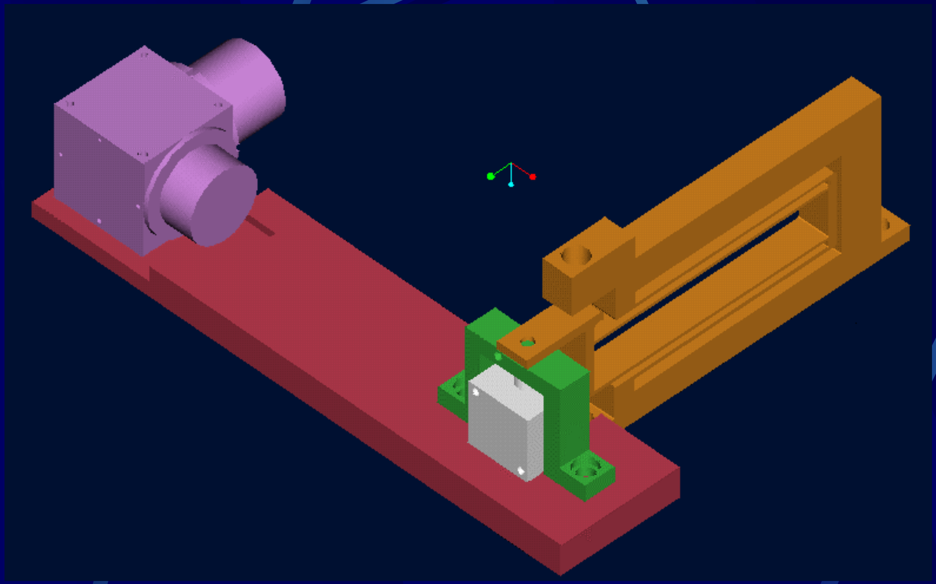


Figure 3: ProEngineer model of the Super Invar mount and flexure for the nanogate.
Purple and Grey: Optics for Zygo interferometer
Red, Green, and Brown: Super Invar flexture and mount

- At nm scales drift due to thermal expansion is a HUGE problem!
- We recorded 225nm/hour thermal drift on a similar Aluminum setup
- We use Super Invar to minimize thermal drift to 30nm/hour
- Actuation and displacement sensing are decoupled (which will be useful in later iterations with integrated actuation and displacement sensing).

Actuation Flexure

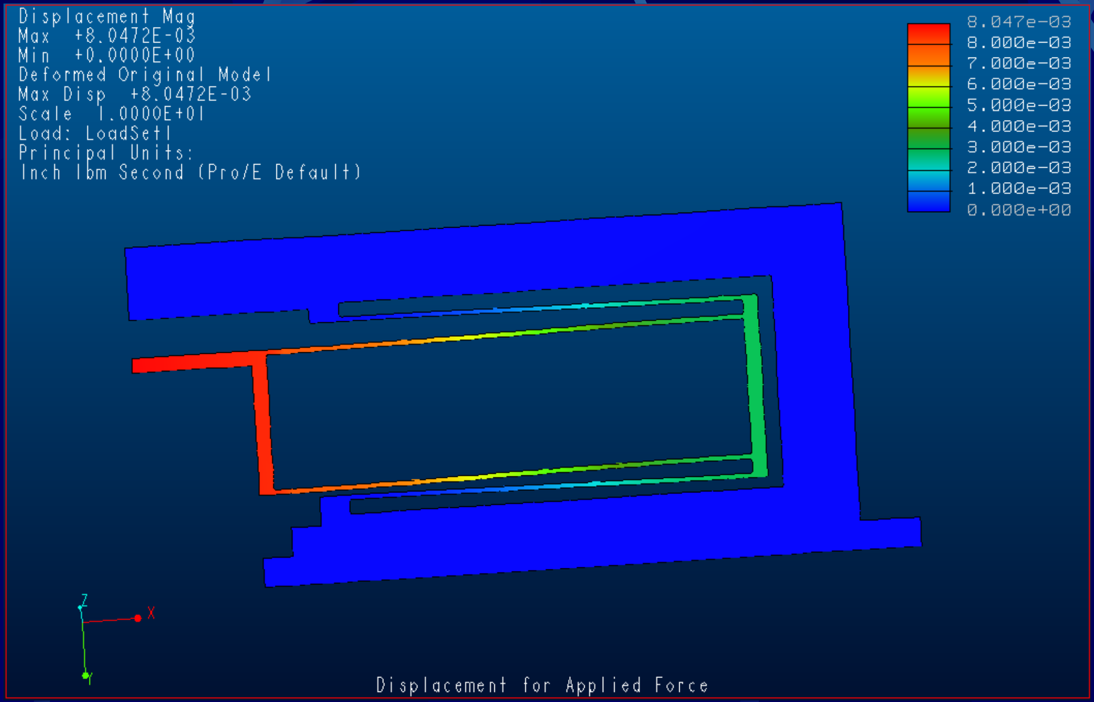
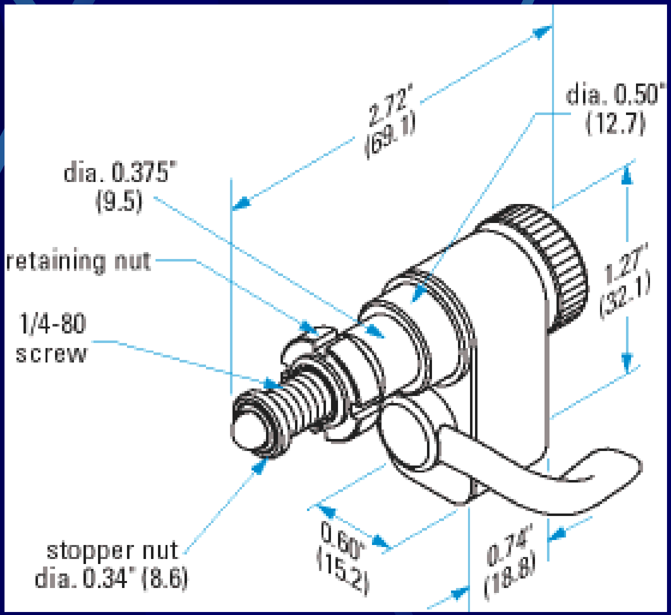


Figure 4: FEM Analysis of Super Invar Flexure

- Super Invar flexure preloads the actuating motor
- Preloading reduces vibration
- Super Invar flexure was fabricated using Prof. Ian Hunter's wire electric discharge machine (EDM)

Picomotor

- Newfocus Picomotor model 8302
- Lead screw actuated by piezoelectric friction drive
- Capable of nm displacement precision, depending on loading



Courtesy Newfocus® www.newfocus.com

Zygo Single Point Optical Probe

- Michelson Inteferometer
- Opto-electronic phase detector to get λ/512 resolution
- 2.4 nm resolution single beam, 1.2nm differential
- 170 micron diameter spot size

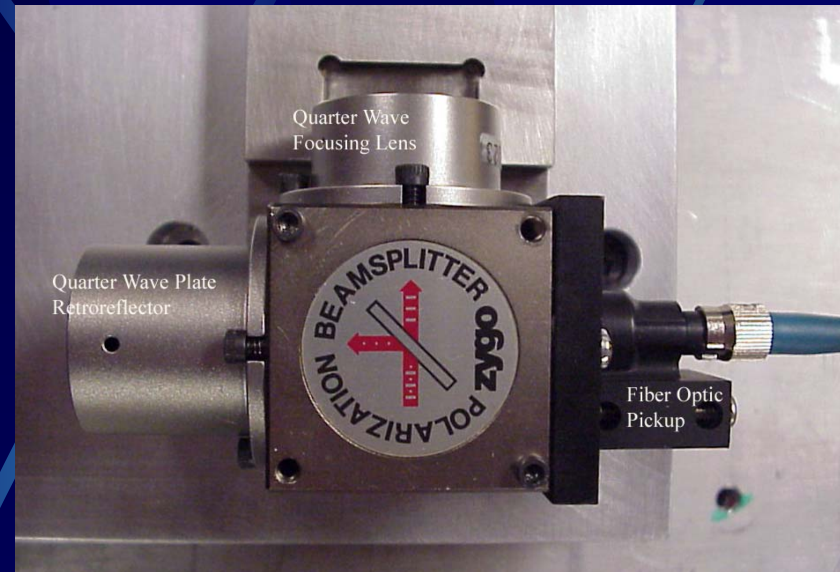
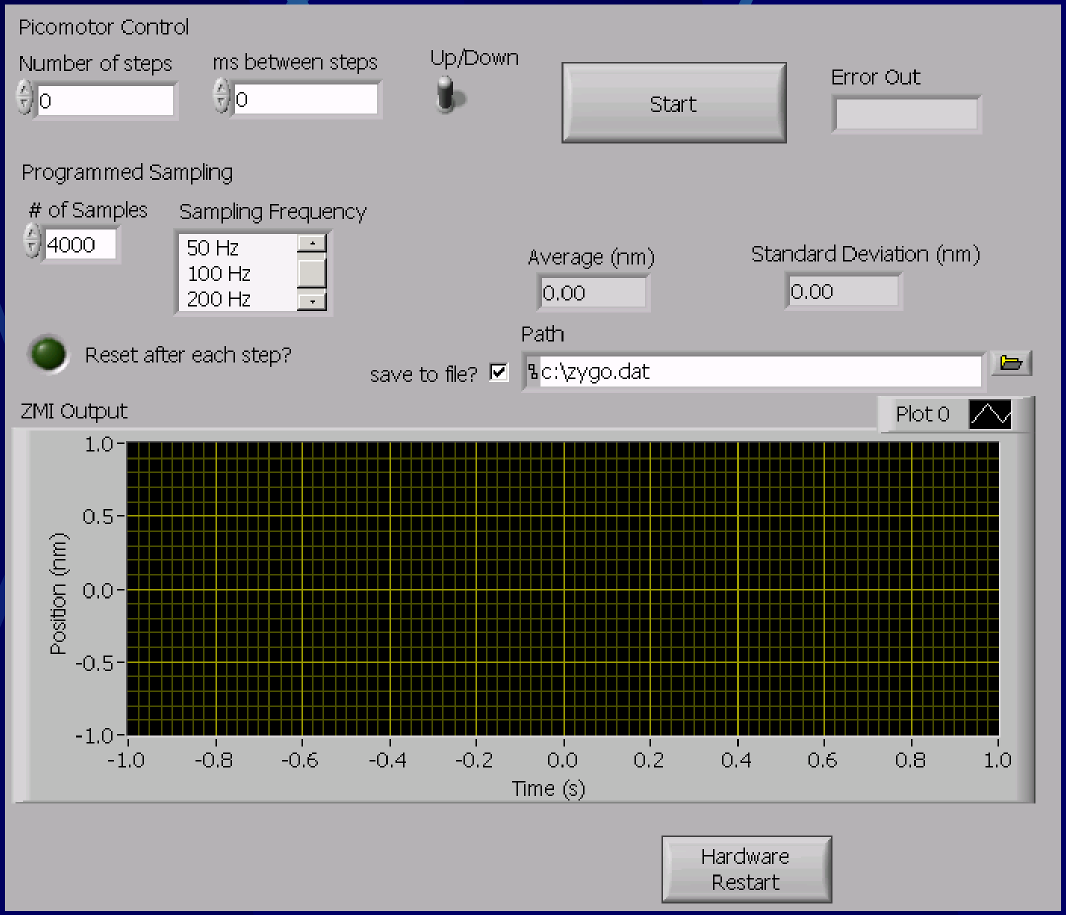


Figure 5: A picture of the Zygo DMI setup

Putting it all together in Labview®

- Controls the Picomotor, Zygo, and syringe pump
- Records up to 4096 samples at 0.1 Hz – 10kHz



Results: Thermal Stability

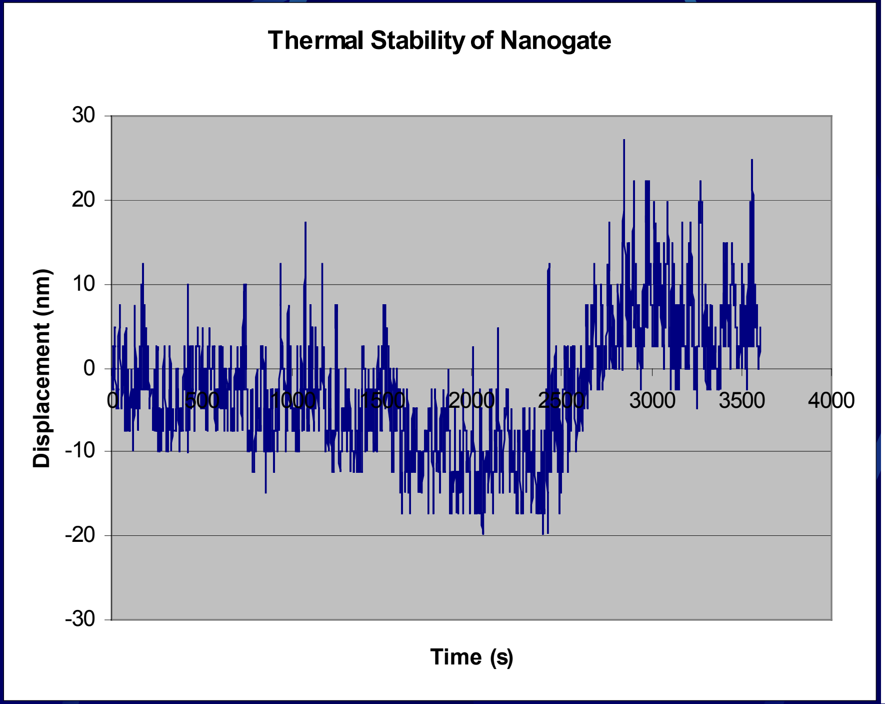


Figure 6: 1 hr. Thermal Stability of Nanogate

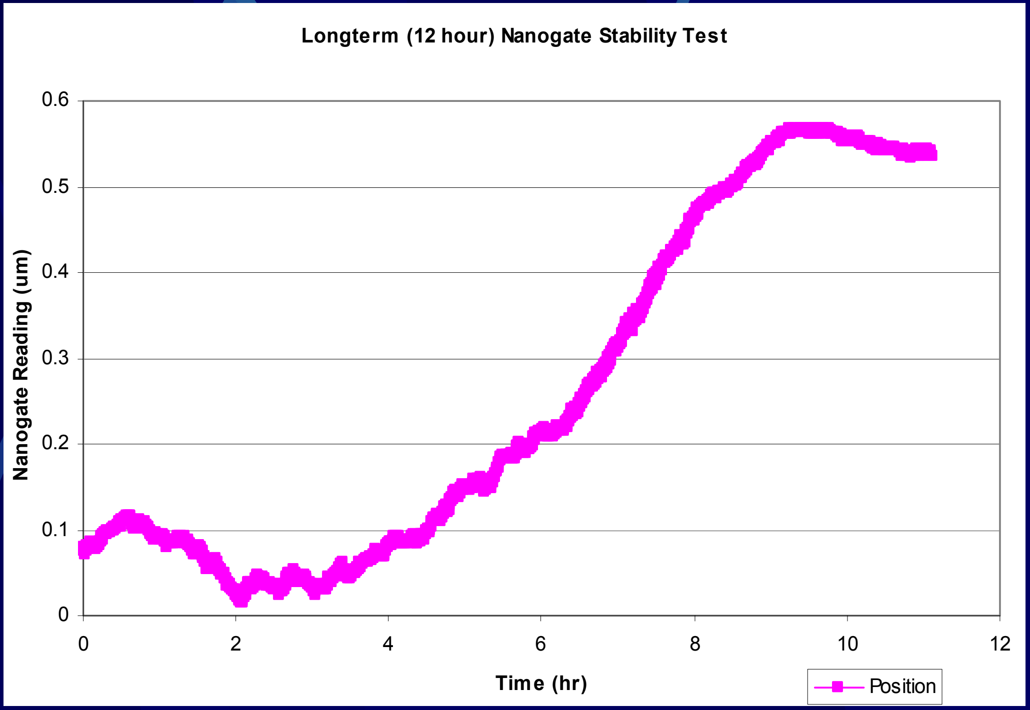
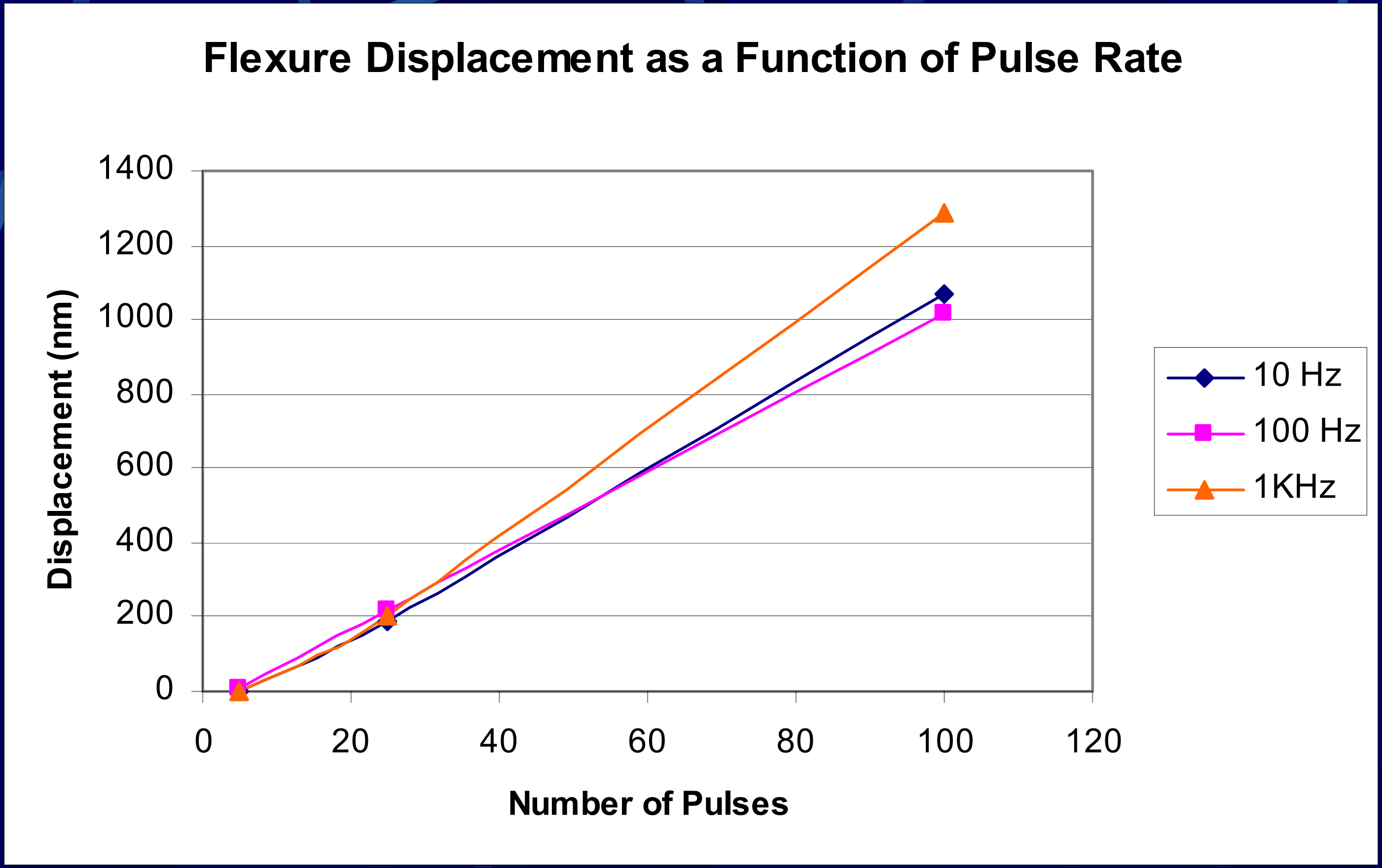


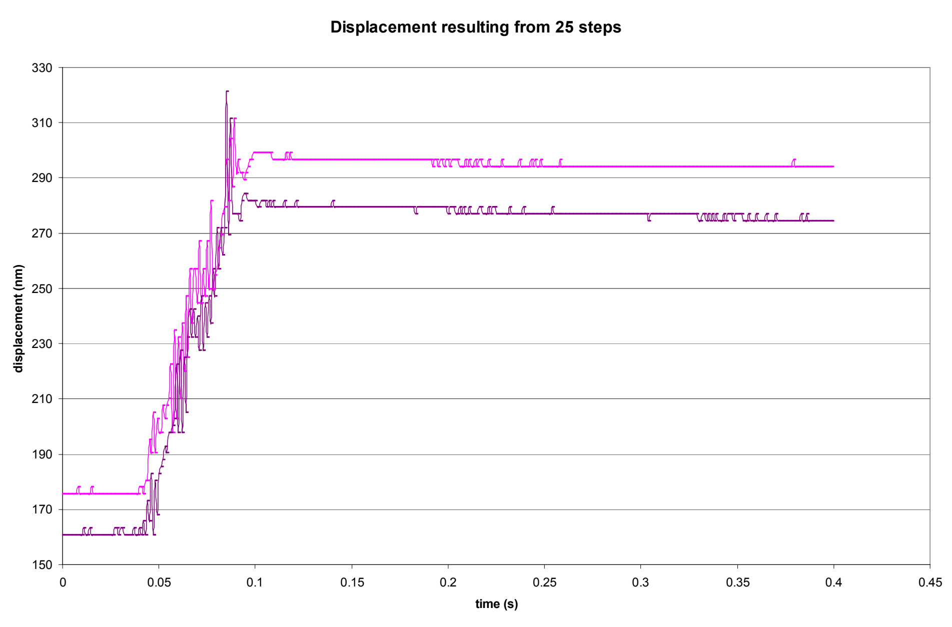
Figure 7: 12-hour Thermal Stability of Nanogate

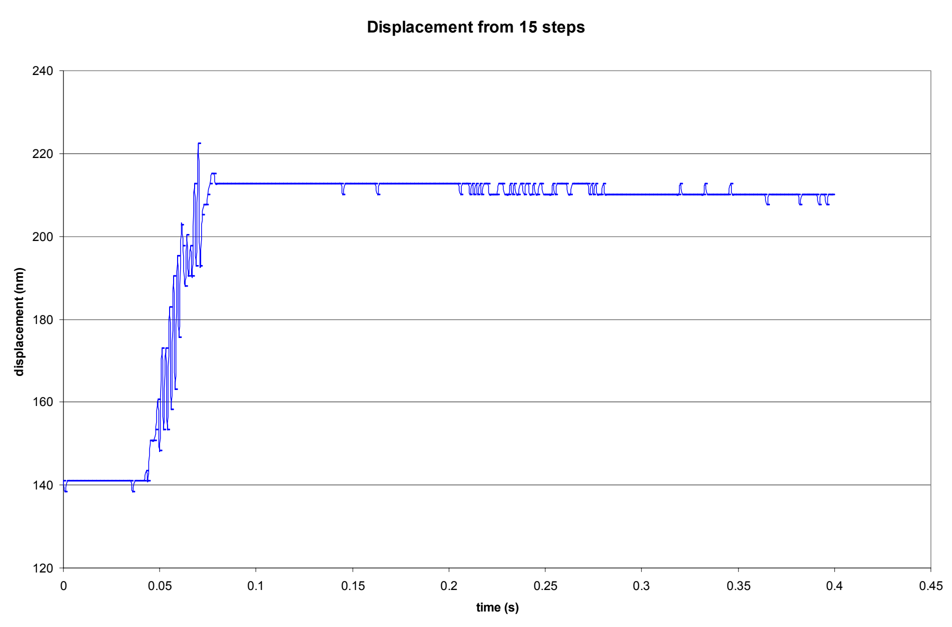
Results: Displacement Calibration

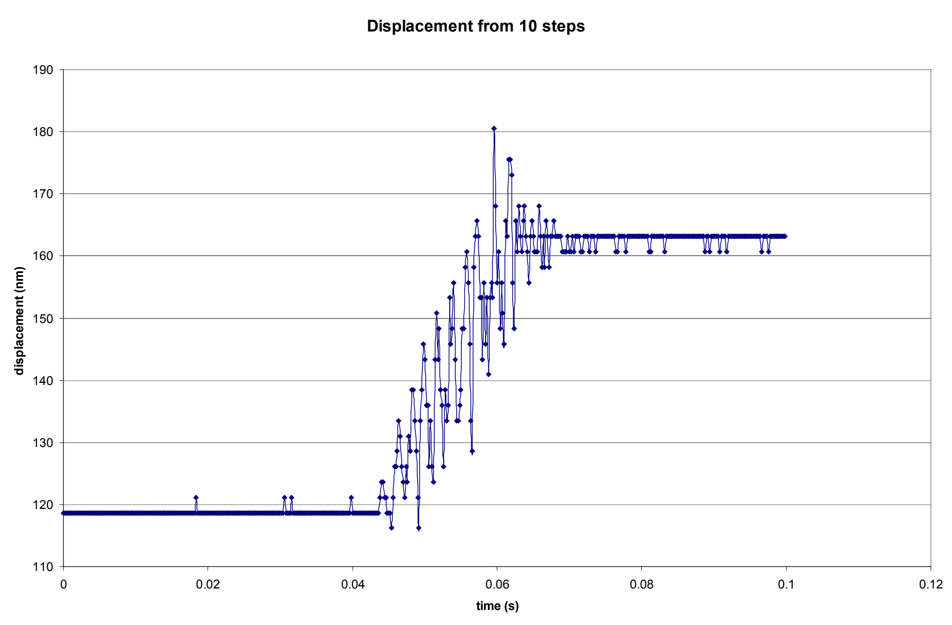


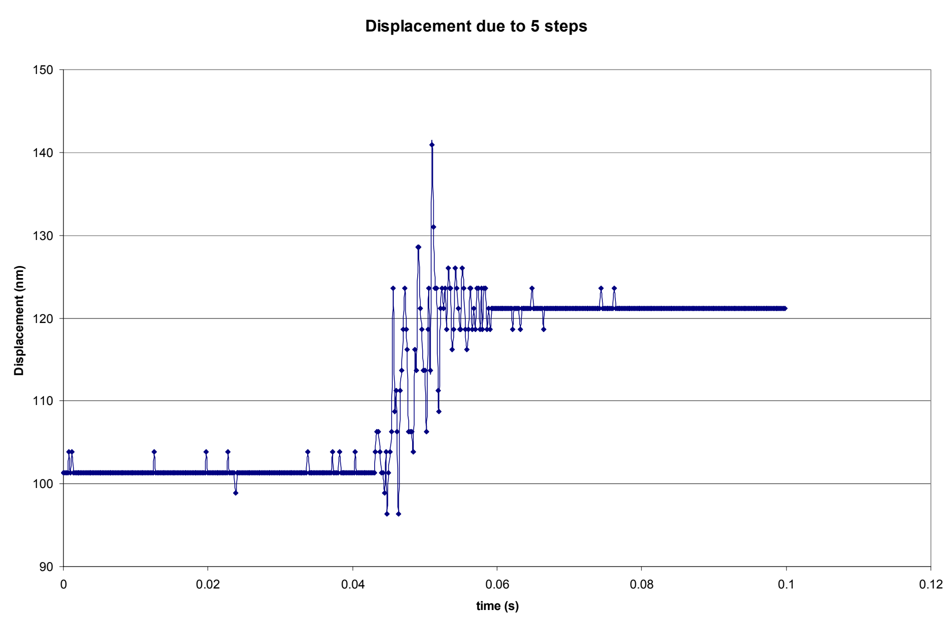
- Faster actuation = more movement.
- First step is wasted.

Results: Opening and Closing the Gate

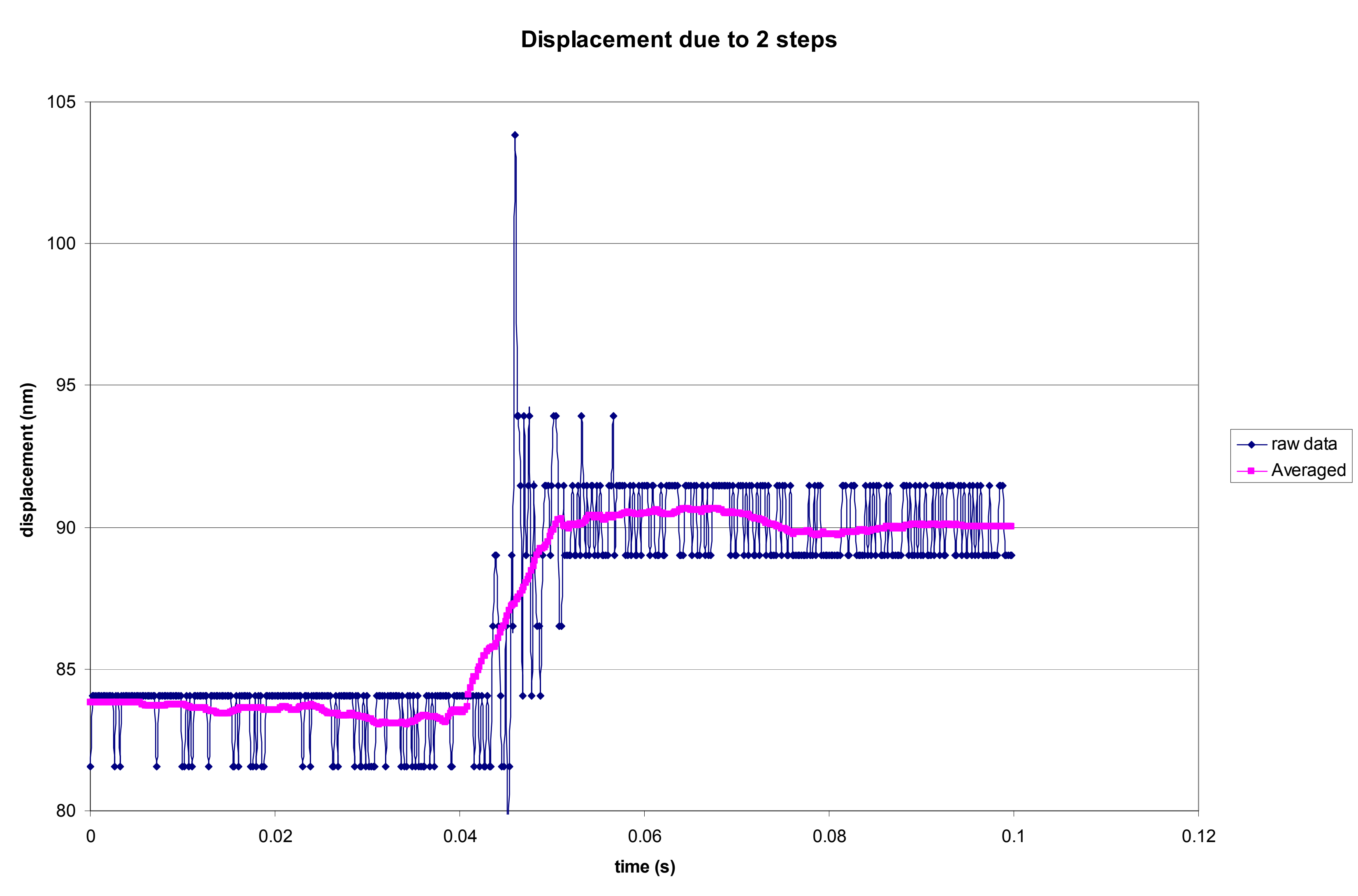




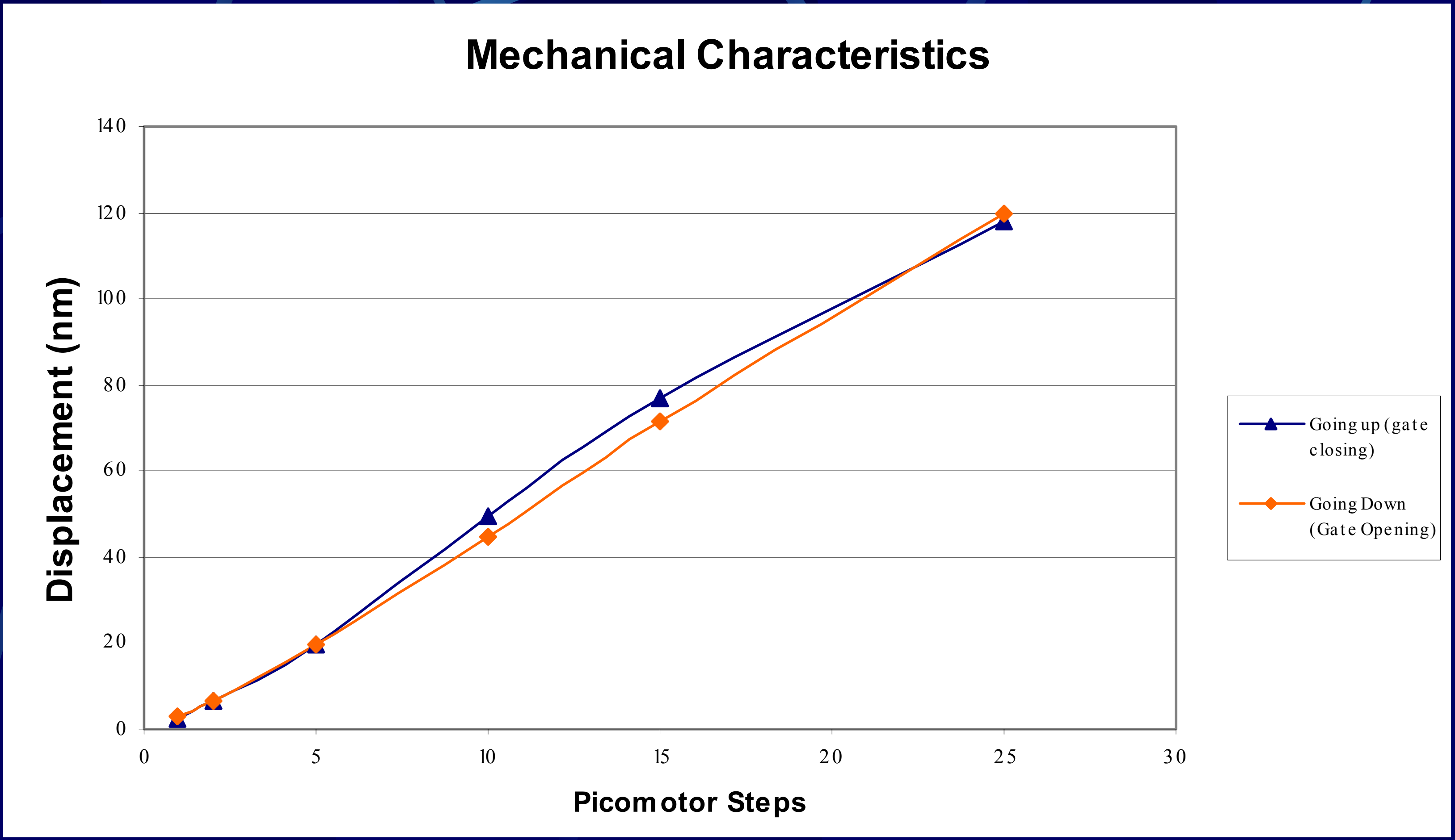




Results: 2nm Resolution!

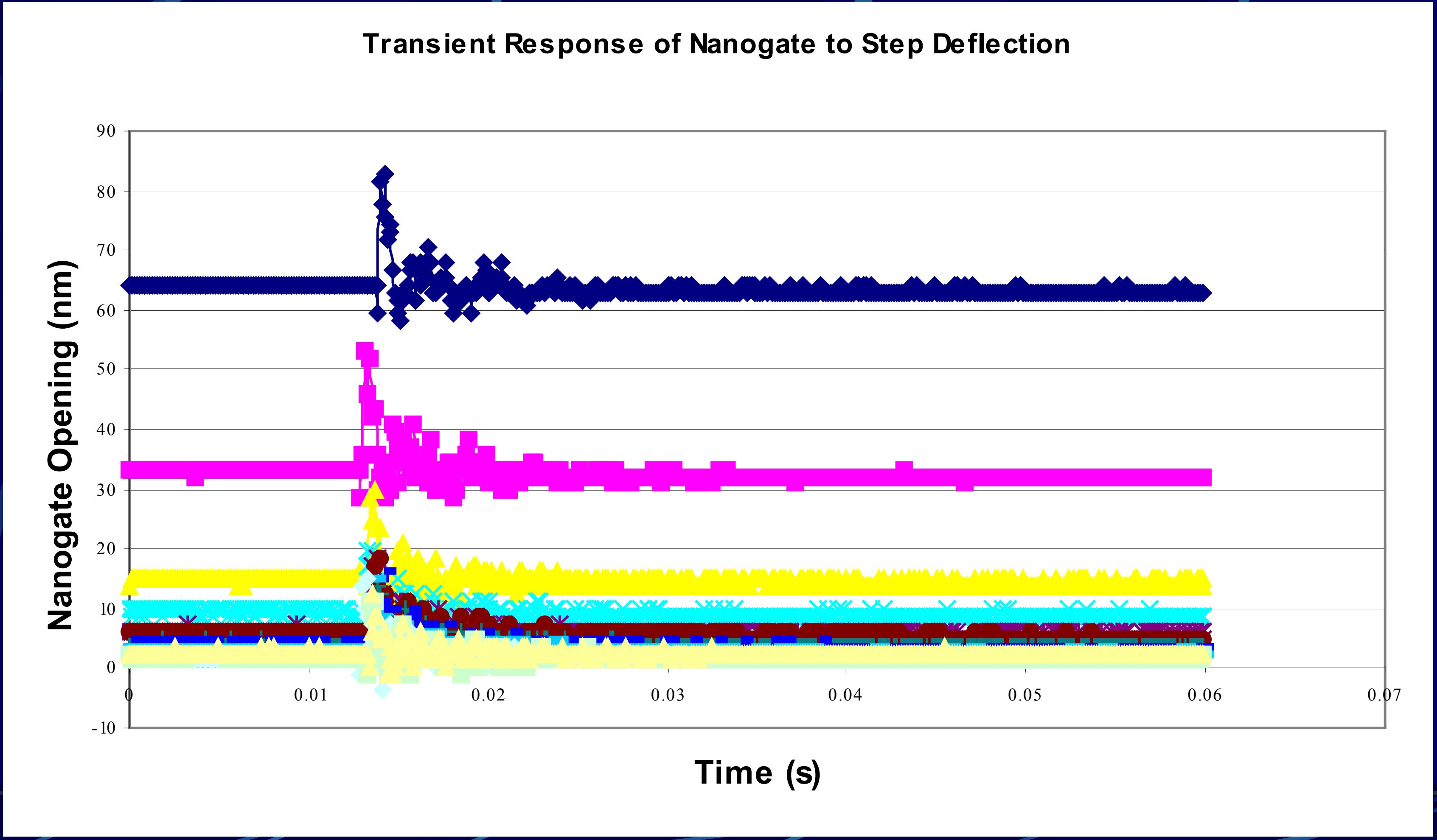


Results: Opening and Closing the Gate

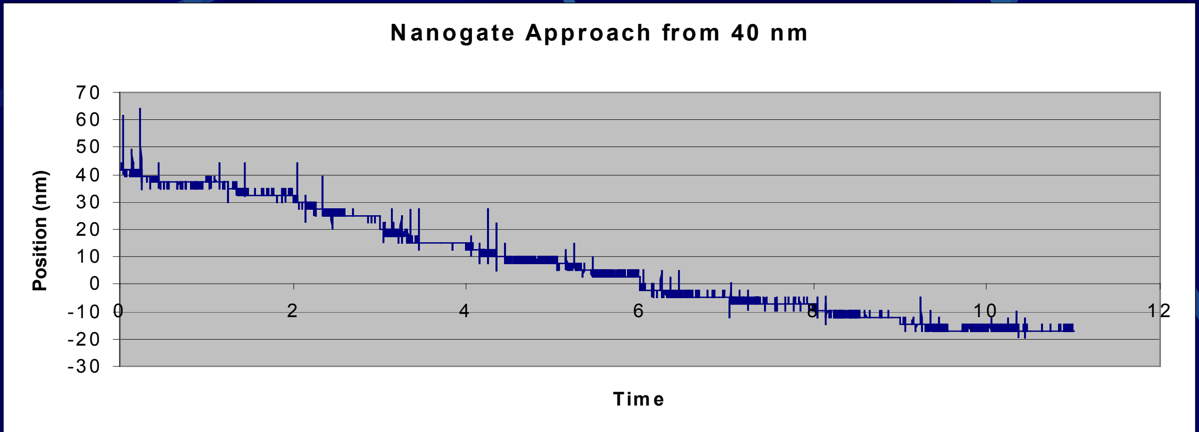


Conclusion: Minimum step size is 2.4 nm

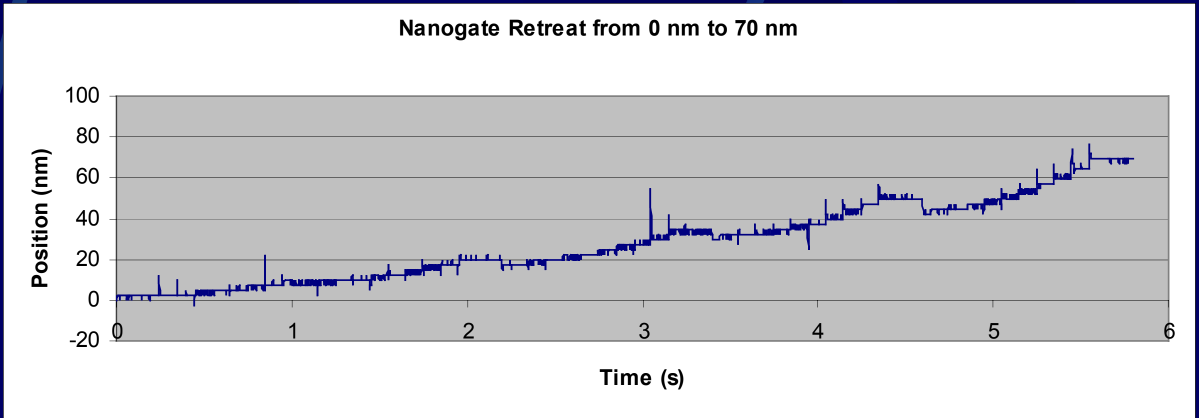
Results: Single-step Transient Response



Approach and Retreat (with no pullin or stiction!)



No pull-in instability was observed during approach



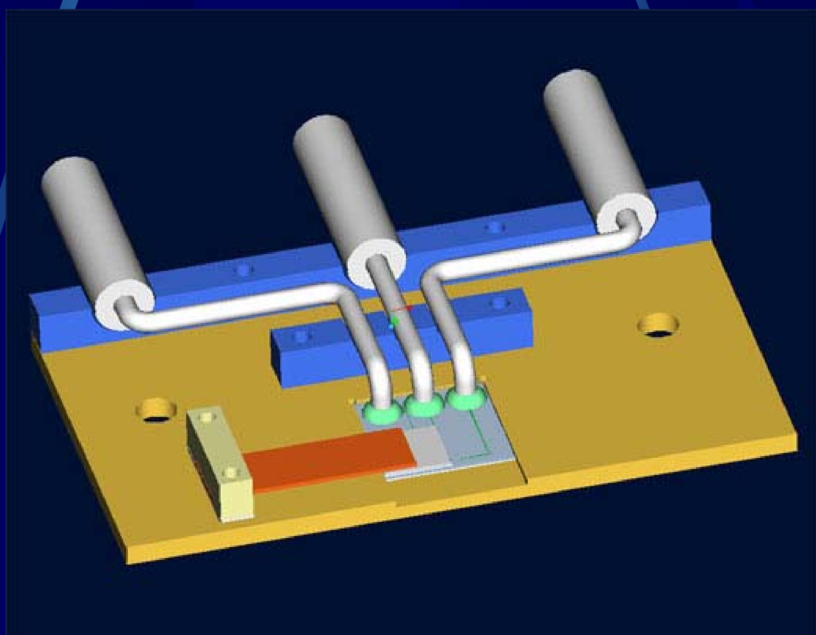
No stiction was observed during retreat

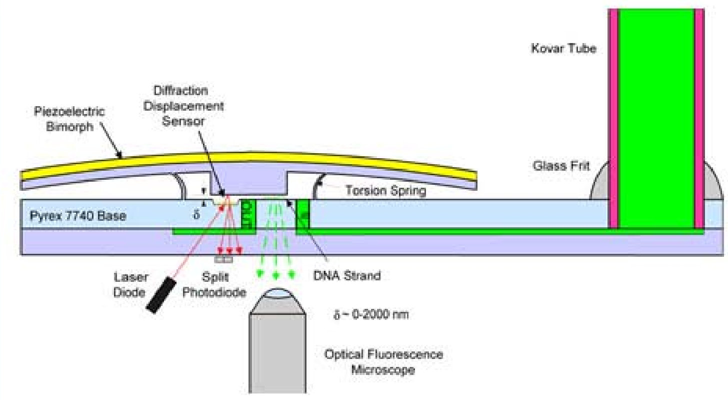
Next Steps for Nanogate Instrumentation

- Fluid connections
- Leak test
- Gold O-rings
- Peltier temperature control
- Integrated Piezoelectric actuator/sensor
- Diffraction-based displacement measurement.
- Fluorescence microscope imaging setup

Packaging The Nanogate

- Multiple functions must be integrated onto a single chip.
- Electrical, fluidic and optical interconnects must be made.
- Each requirement imposes constraints.





Above: Schematic Cross-Section of Nanogate.

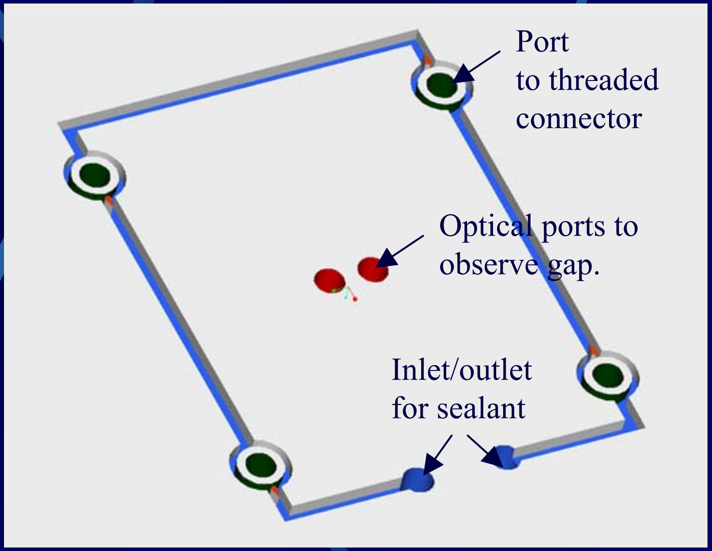
Left: Packaged Nanogate with Piezoelectric Bimorph Actuator Integrated Leak Sensor and VCR fittings.

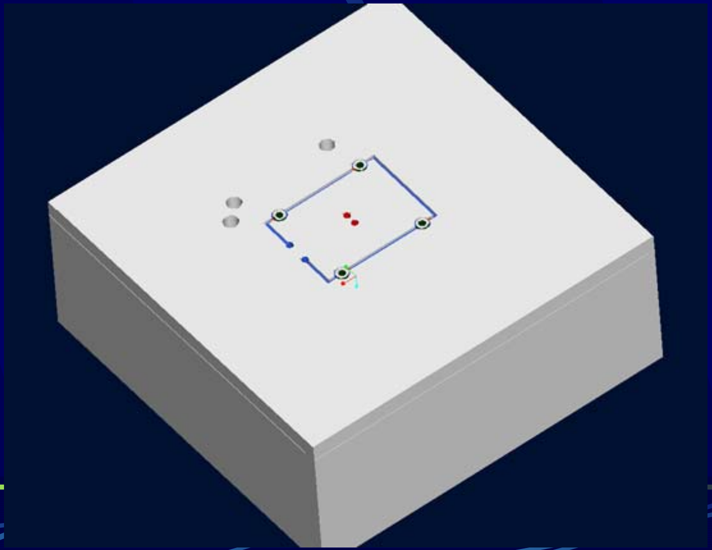
Fluid Packaging

- Requirements:
  - Pressure range from vacuum to 10 atm.
  - Arbitrary liquids or gases: Helium, Air, Water, Benzene.
  - Simple connection to VCR-4 fittings for Helium leak test.
  - Reliable connection to chip through 0.5 mm Pyrex wafer.
  - Do not transfer vibrations or loads to chip.
- Solution:
  - Ultrasonically drilled Pyrex glass wafer.
  - Frit bonded 1/8” Dia. Kovar tubing to Pyrex glass.
  - Epoxy strain relief fitting on package.

Fluid Package

- A generic, commercially available, microfluidic package element does not exist.
- For the Nanogate, a vacuum-compatible stainless steel package, in-situ seal (formed with leak sealant), and threaded connections will be used (made with conventional machining and EDM).
- In other applications, an anodically-bonded package could be appropriate.



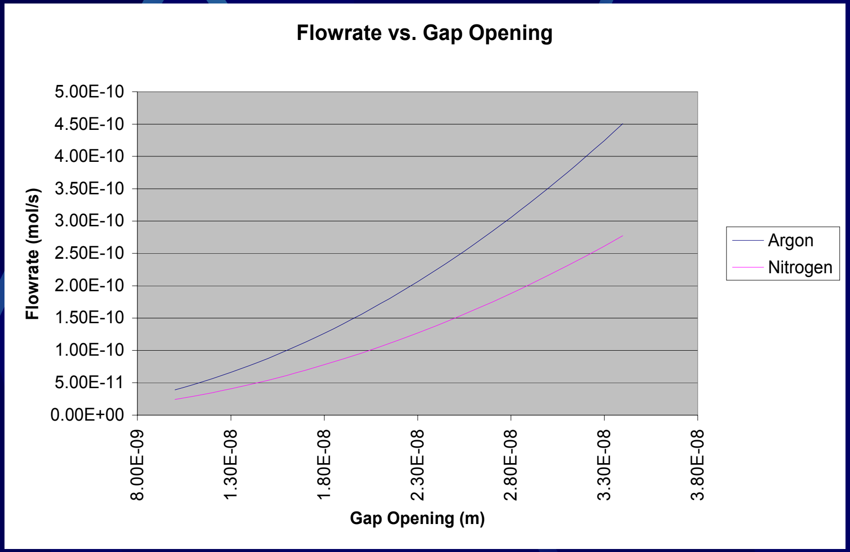


Future Work

- Fundamental physics of fluid flow: does slip flow exist?
- Filter fluorescent tagged polystyrene spheres.
- Coat surfaces with silane or thiol self-assembled monolayers to engineer adsorption properties.
- Filter bio-molecules such as protein and DNA (controllable nano-pore).

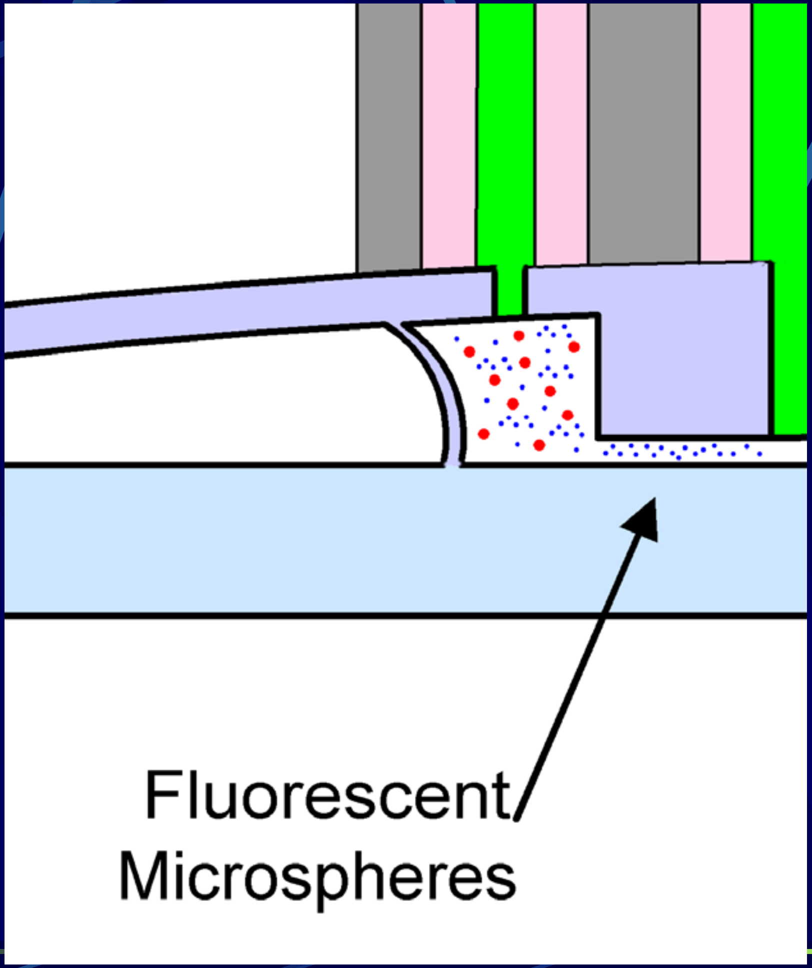
Gas Flowrate

- The gas flowrate in a small channel has an additional dependence on the weight of the molecule.
- In a long, narrow channel, this effect can be exploited to form a gas filter (e.g. to separate Tritium from Helium)



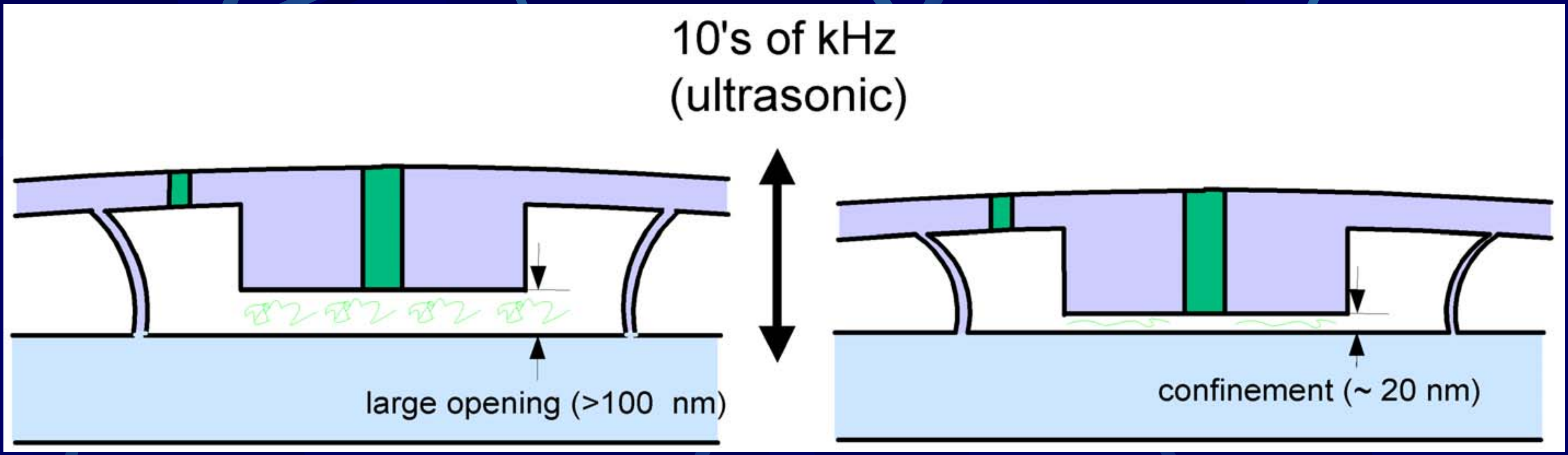
$$\frac{\dot{m}}{\Delta P} = \frac{H^3 w}{12\mu LRT}\bar{P} + \frac{H^3 w}{2\mu LRT}\frac{2-\sigma_m}{\sigma_m}K_o P_o$$

Molecular Sieve



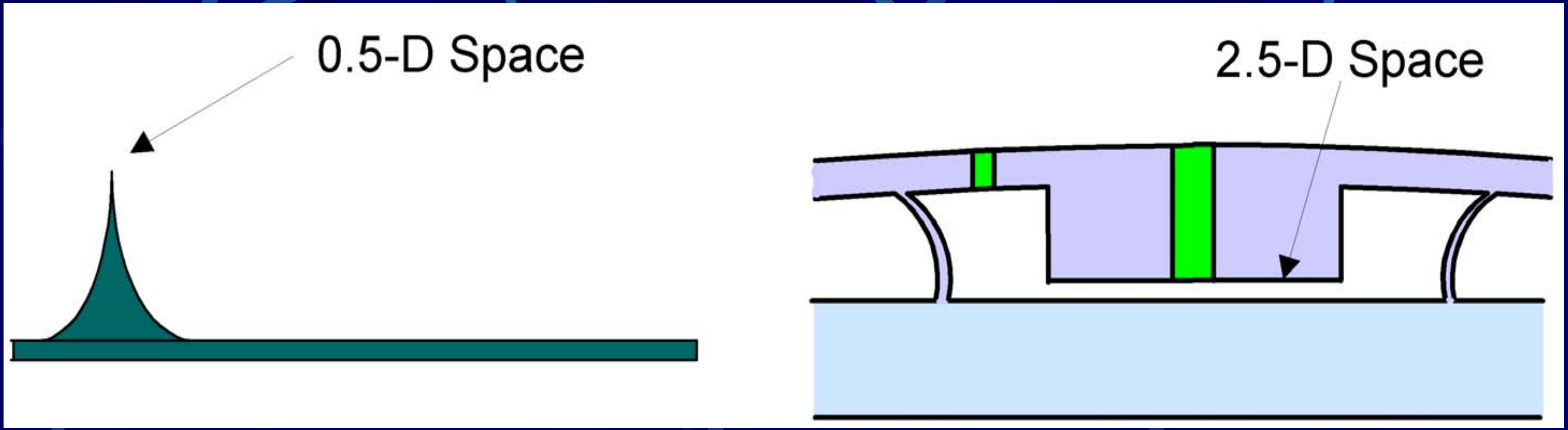
- Flowrate of large molecules is nonlinearly dependent on the gap size, and modulation frequency, for very small gaps
- How does the mobility of a protein depend on the size and surface properties of the channel?
- Can proteins be mechanically filtered based on size?
- Can adsorption be controlled?

Entropic Trap
Filter DNA by Size



- Flowrate of large molecules is nonlinearly dependent on the gap size, and modulation frequency, for very small gaps
- Does the mobility depend on the relaxation time from coiled to flat?
- How does the mobility of a protein depend on the size and surface properties of the channel?

Technology Comparison



- The AFM employs a 0.5-dimensional probe to investigate molecular phenomena in an unperturbed state (or to molecules atoms individually)
- The Nanogate provides a highly confined environment – molecules are constrained in a 2.5- dimensional space.

Conclusions

- Macroscopic, off-chip actuators and optical displacement sensors can provide high resolution control for experimental purposes.
- Near-term experimental results will demonstrate the Nanogate's ability to control minute gas flows, separate gases by molecular weight, and control tiny liquid flows.
- The flow of pure liquids in non-wetting channels, under confinement, will be studied to verify (or refute) evidence of a "slip" boundary condition in these conditions.
- The handling of tiny samples of DNA will be a focus of later work (H. Ma).

Acknowledgements

- Thanks to Hong Ma for assistance with software and testing the Nanogate.
- James White gratefully acknowledges the support of the Hertz Foundation.
- The Nanogate was funded by the NSF.