Designing Piezoelectric Micro-actuators Using COMSOL

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Agenda

- Introduction
- Piezoelectric MEMS Design
- Numerical Models
- Experimentation
- Results
- Conclusion

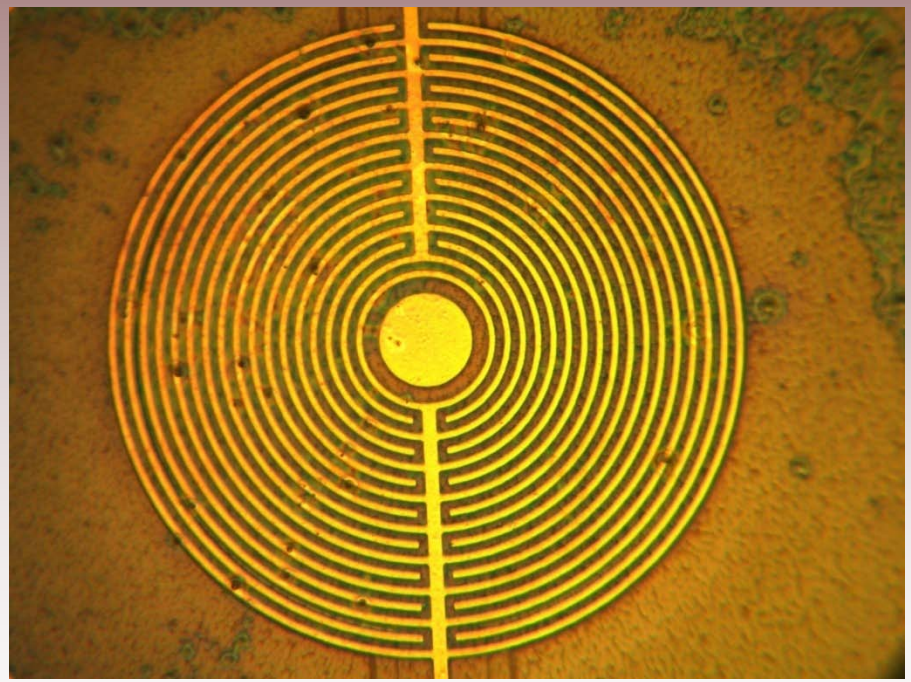
Introduction

Planar Sandwich

d_{31} actuation

Interdigitated

d_{33} actuation



d_{33} – piezoelectric coupling (~ $3|d_{31}|$)

Piezoelectric MEMS Design Parameters

- Piezoelectric Thickness
- Center Disk Diameter
  - Design Parameter Coupling
- Physical Boundary Conditions
- Electrode Width
- Electrode Separation (Pitch)
- Number of Electrodes
  - Separate or Design Parameter Coupling
- Voltage Polarity

Numerical Modeling

Interdigitated Actuator Pre-Processing

Material	Thickness (μm)	Young's Modulus (GPa)	Poisson's Ratio	Density (kg/m^3)
Gold	0.5	80	0.42	19280
ZrO_2	0.4	86	0.27	4600
SiO_2	0.7	74.5	0.17	2200
Al_2O_3	0.25	376.91	0.24	3895

- Geometry
  - Diameter = 700 μm
- Assumptions
  - 2D axi-symmetric model with symmetric boundary conditions

- PZT-5H
  - Stiffness Matrix

$$c = \begin{bmatrix} 126 & 79,5 & 84,1 & 0 & 0 & 0 \\ & 126 & 84,1 & 0 & 0 & 0 \\ & & 117 & 0 & 0 & 0 \\ & & & 23,3 & 0 & 0 \\ & sym & & & 23,0 & 0 \\ & & & & & 23,0 \end{bmatrix} GPa$$

  - Piezoelectric Coupling Constants

$$e = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 17 \\ 0 & 0 & 0 & 0 & 17 & 0 \\ -6,5 & -6,5 & 23,3 & 0 & 0 & 0 \end{bmatrix} \frac{C}{m^2}$$

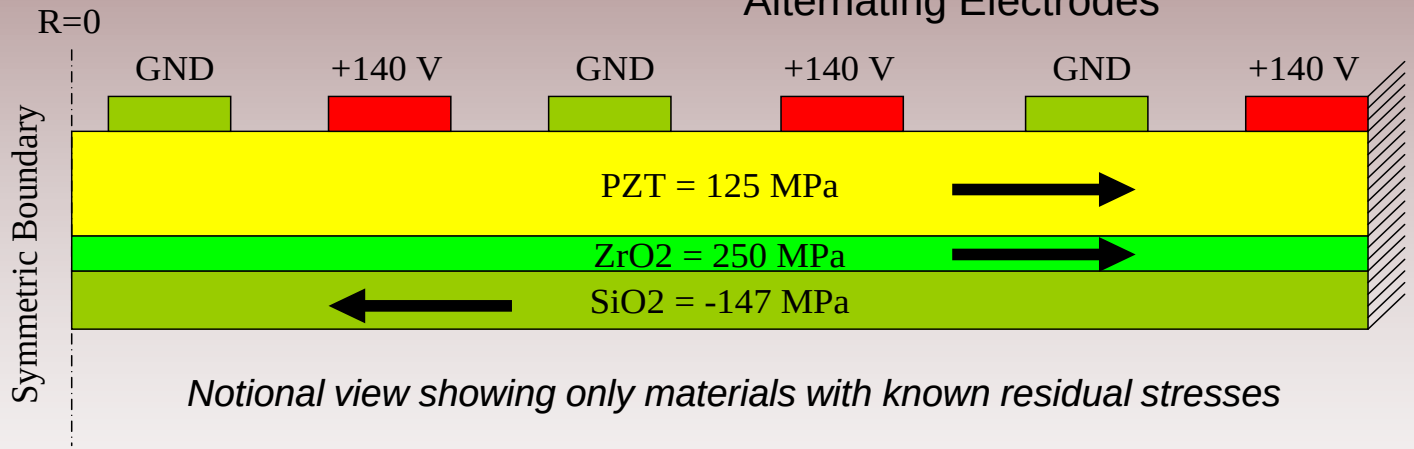
  - Permittivity Constants

$$\varepsilon = \begin{bmatrix} 1,503 & 0 & 0 \\ 0 & 1,503 & 0 \\ 0 & 0 & 1,3 \end{bmatrix} \times 10^{-8} \frac{F}{m}$$

Numerical Modeling
Interdigitated Actuator Pre-Processing

- Symmetric Constraint Boundaries on center radius
- Clamped BC on External Radius
- d_{33} – piezoelectric coupling (~ $3|d_{31}|$)

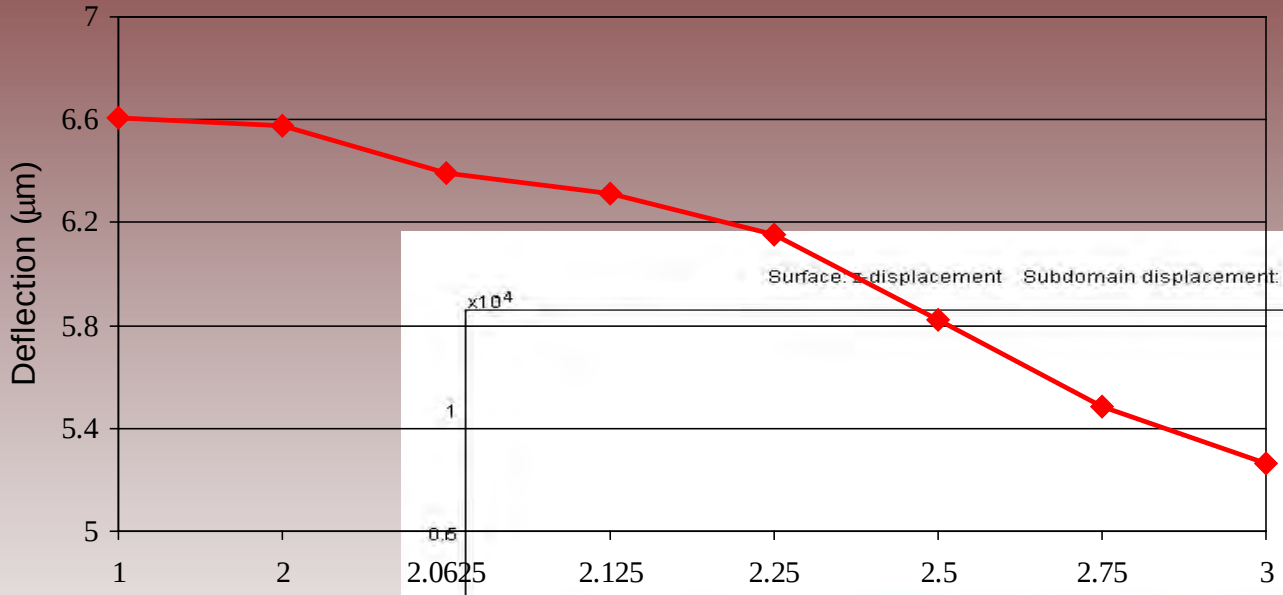
- Design Considerations
  - Positive electrode on clamped circumference
  - Applied Voltage = 140 VDC (500mA) on Alternating Electrodes



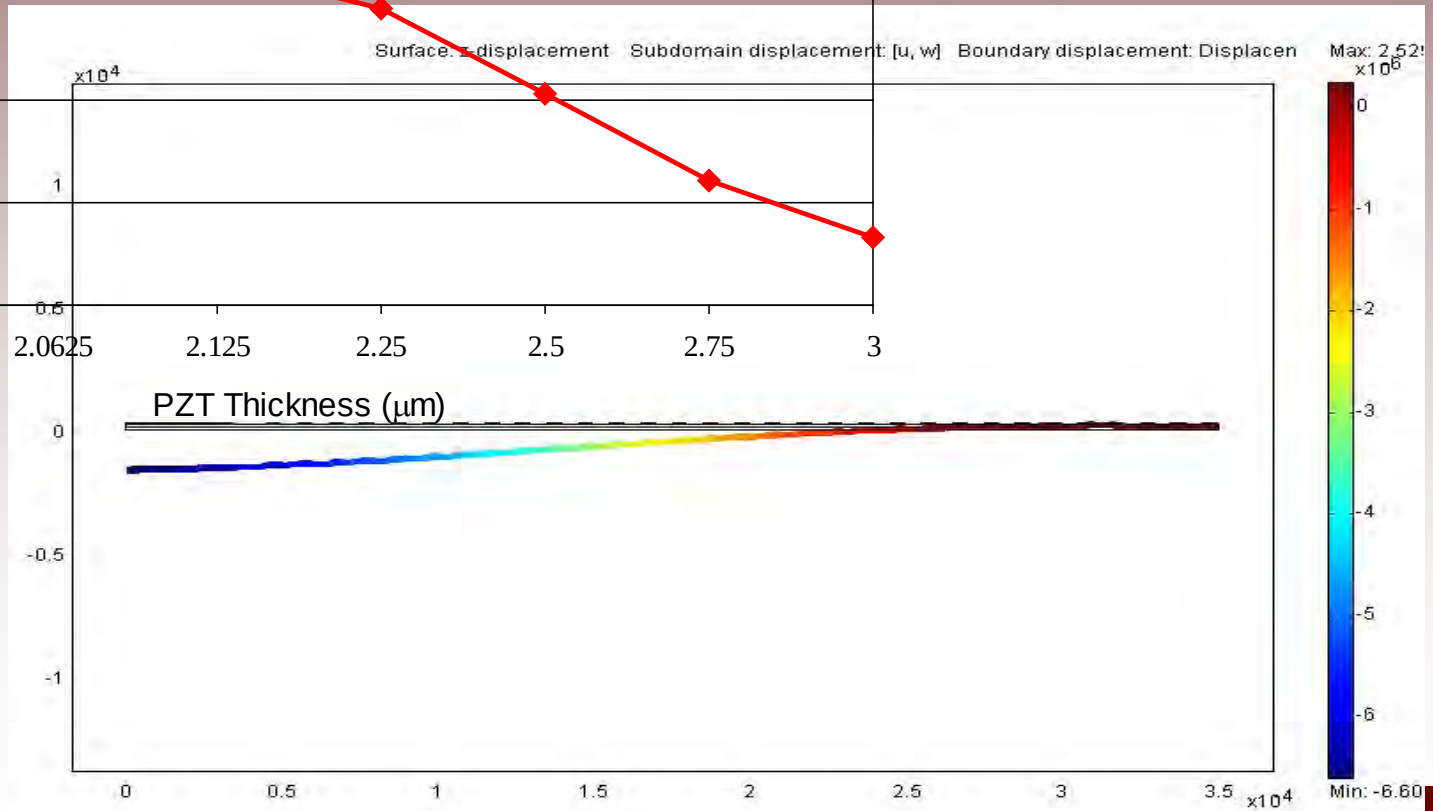
Notional view showing only materials with known residual stresses

Spin Coated & Annealed Processing for PZT and ZrO_2
- Low temperature deposition of SiO_2
- Processing stack-up tolerance ~ 0.6 – 0.9μm

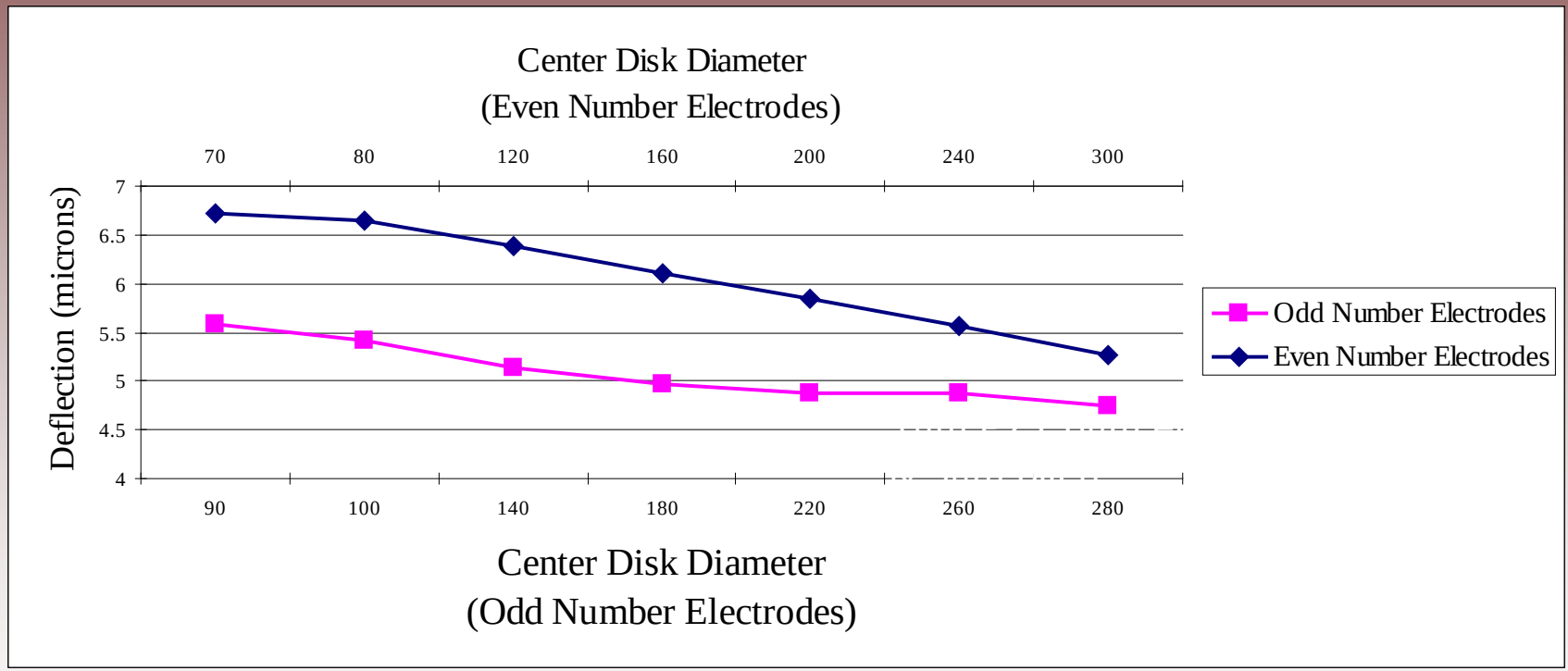
Design Parameters
Deflection vs. PZT Thickness



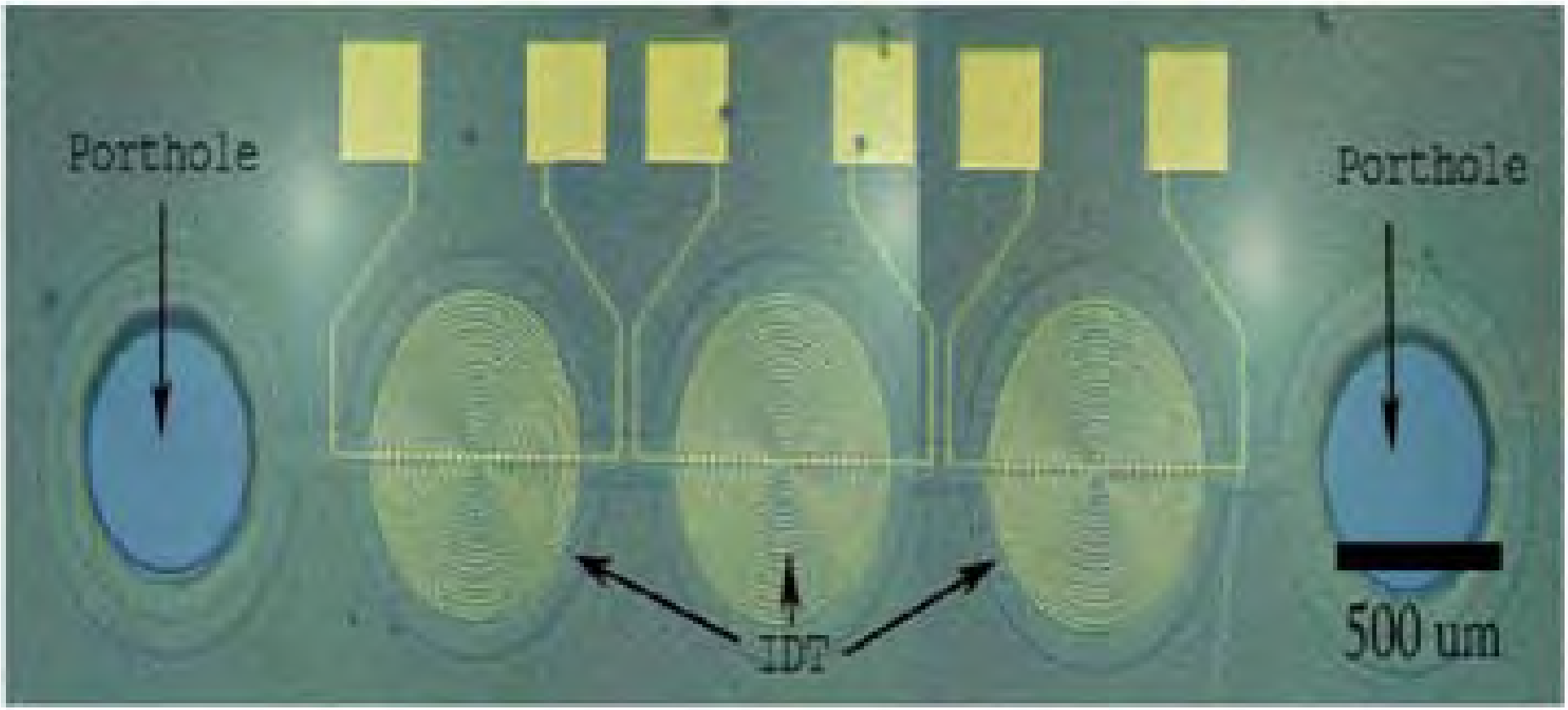
1μm PZT 6μm electrode width & 5μm pitch



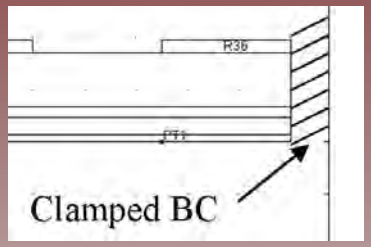
Design Parameters
Deflection vs. Center Disk Diameter

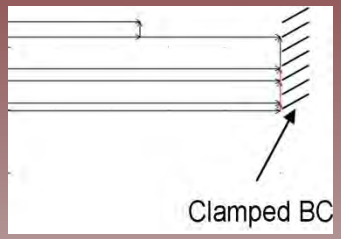


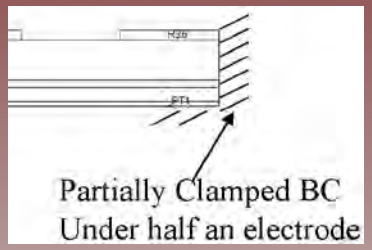
Piezoelectric MEMS Design - Electrode Boundary Position

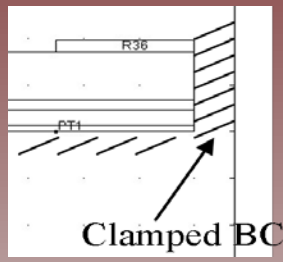


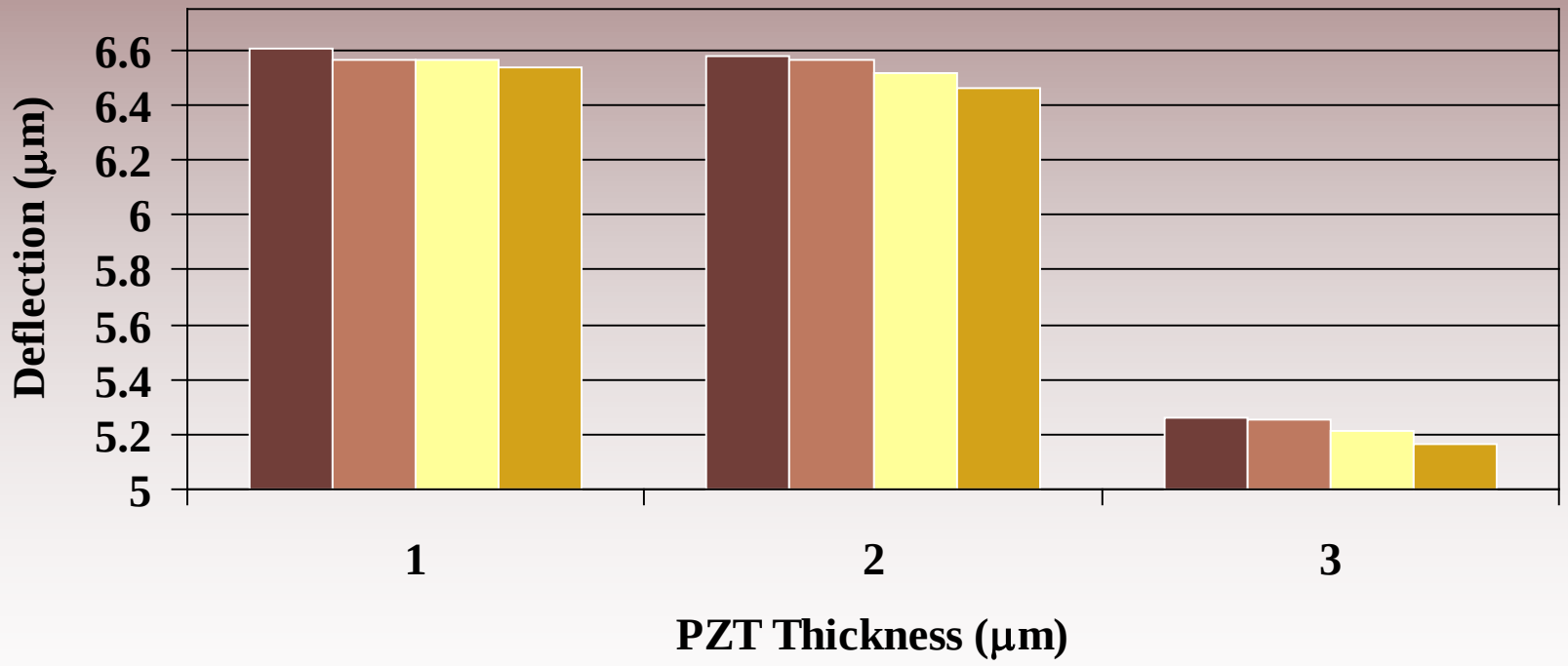
Design Parameters
Deflection vs. Electrode Position/Boundary Conditions



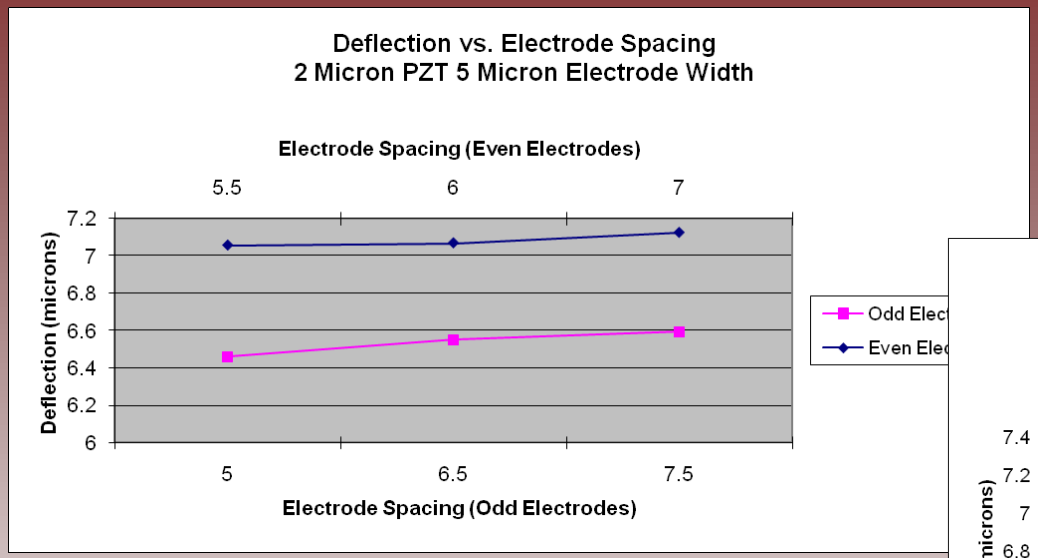


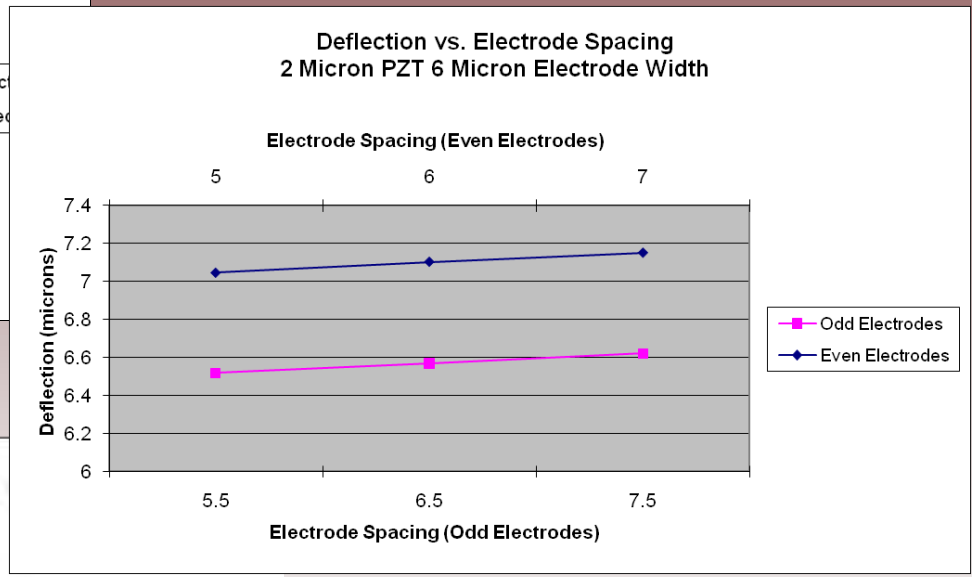


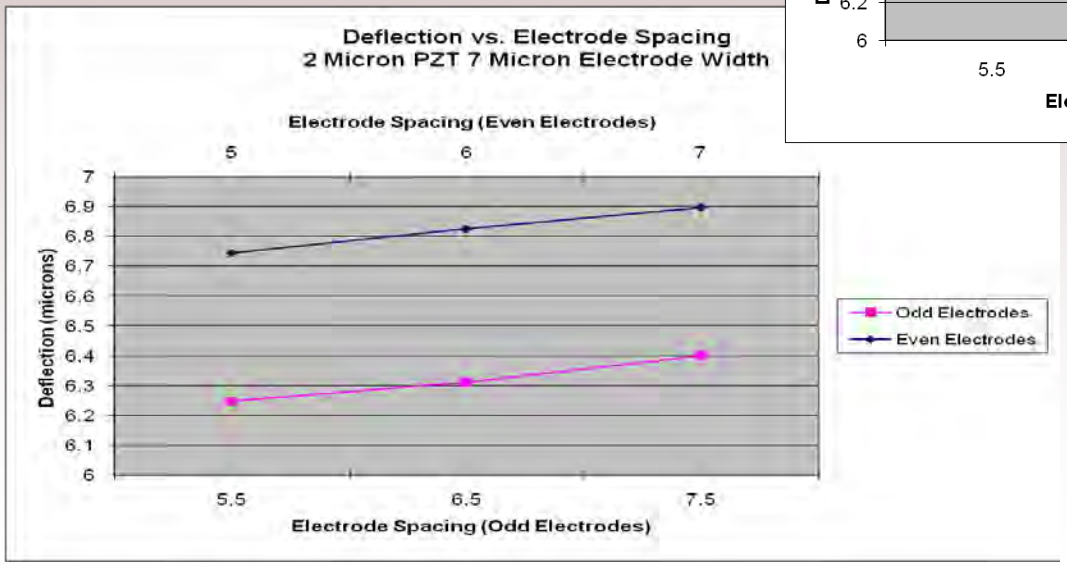




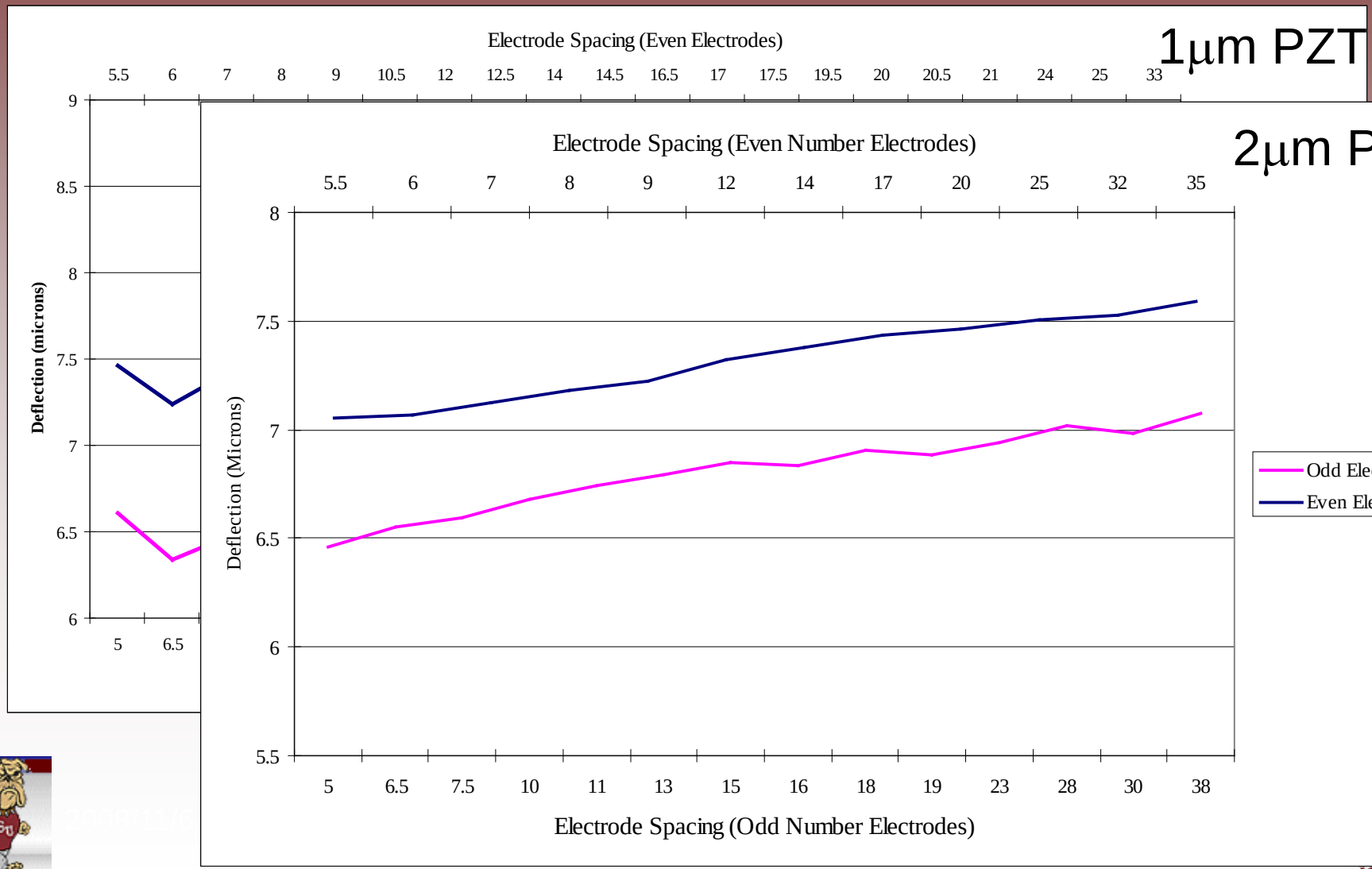
Piezoelectric MEMS Design
Electrode Width







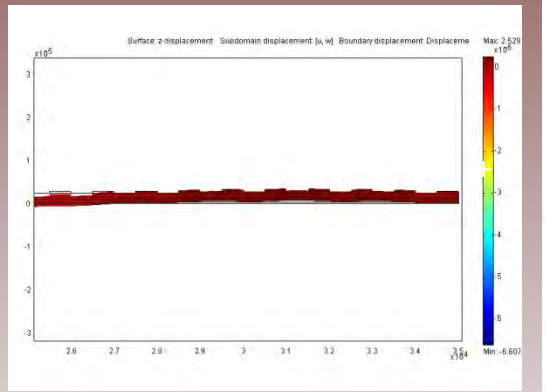
Design Parameters
Electrode Separation Simulation

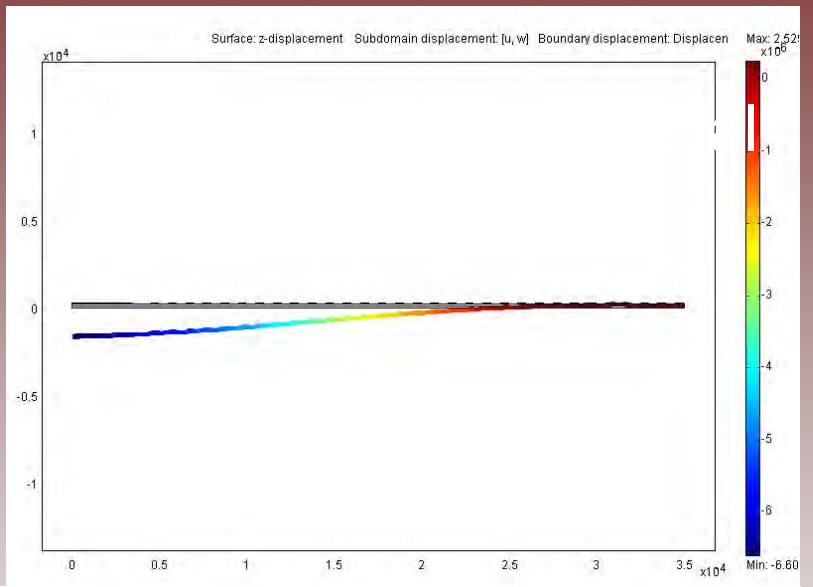


Design Parameters
Electrode Polarization (1μm PZT)

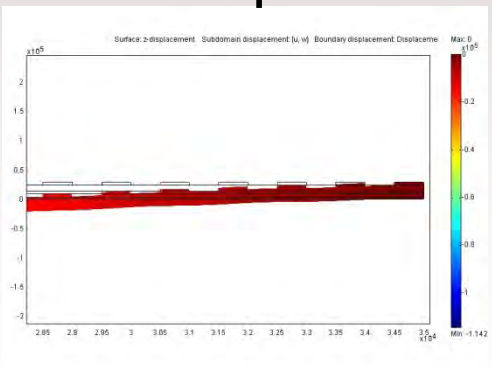
Positive Electrodes on Clamped End

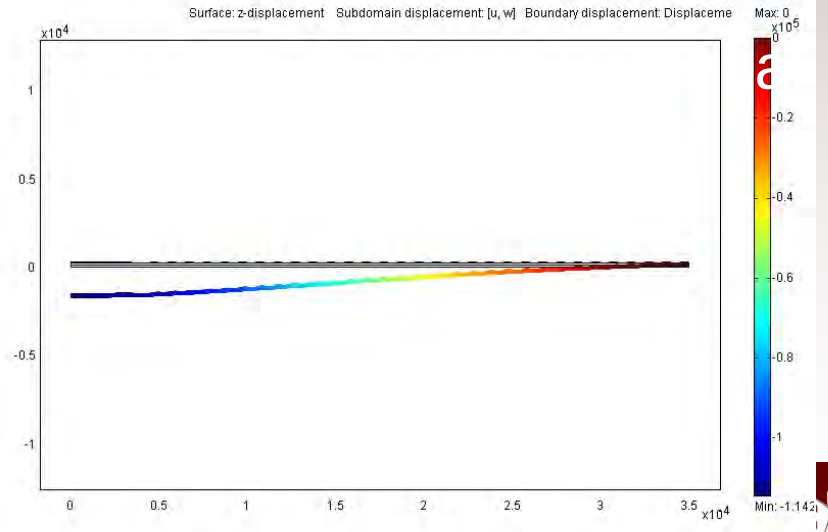
- Flush Electrodes
- 70 μm Center Disk
- 5 μm Electrode Width
- 5 μm Electrode Spacing
- 1 μm PZT





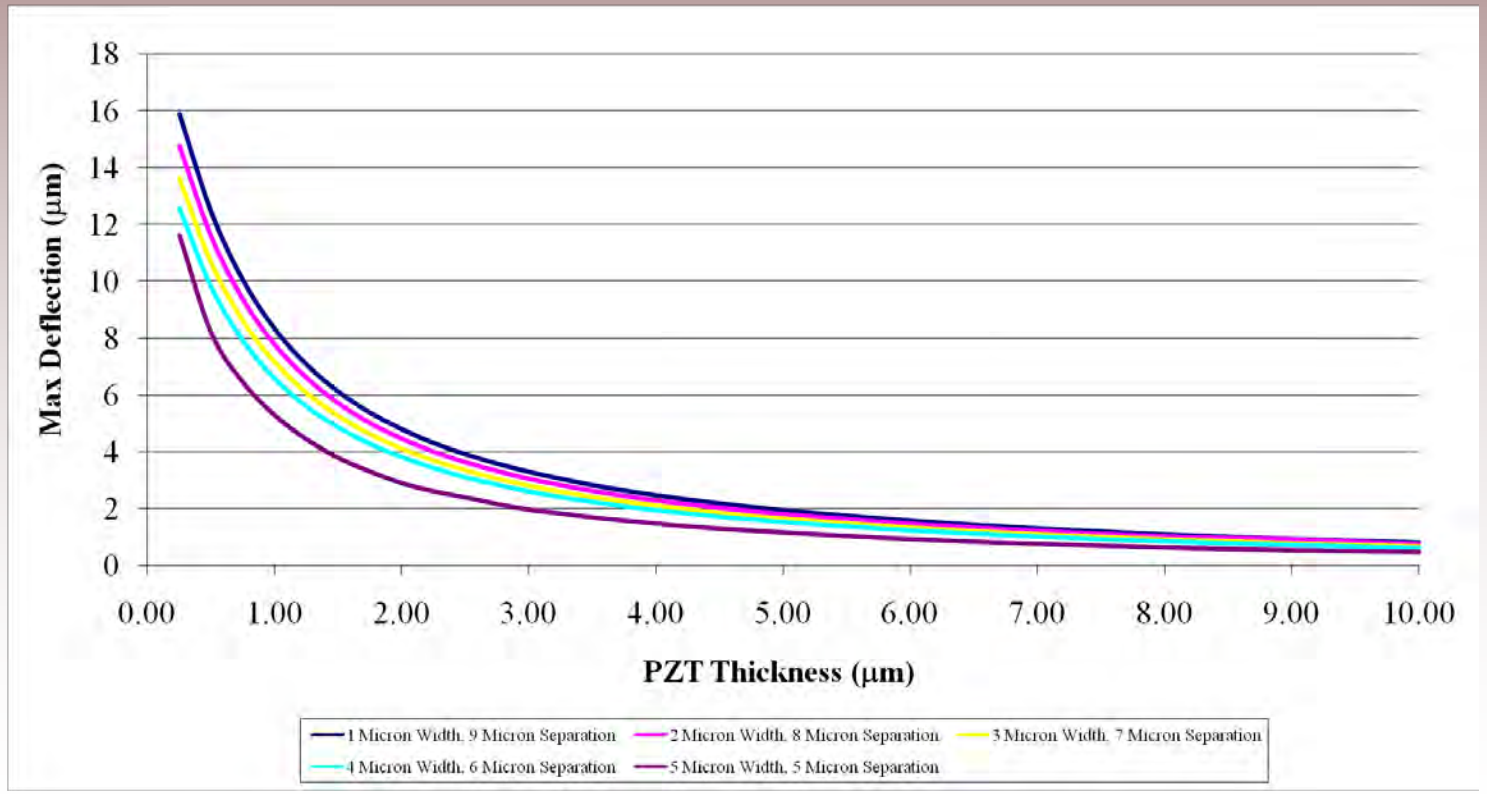
Ground Electrodes on Clamped End





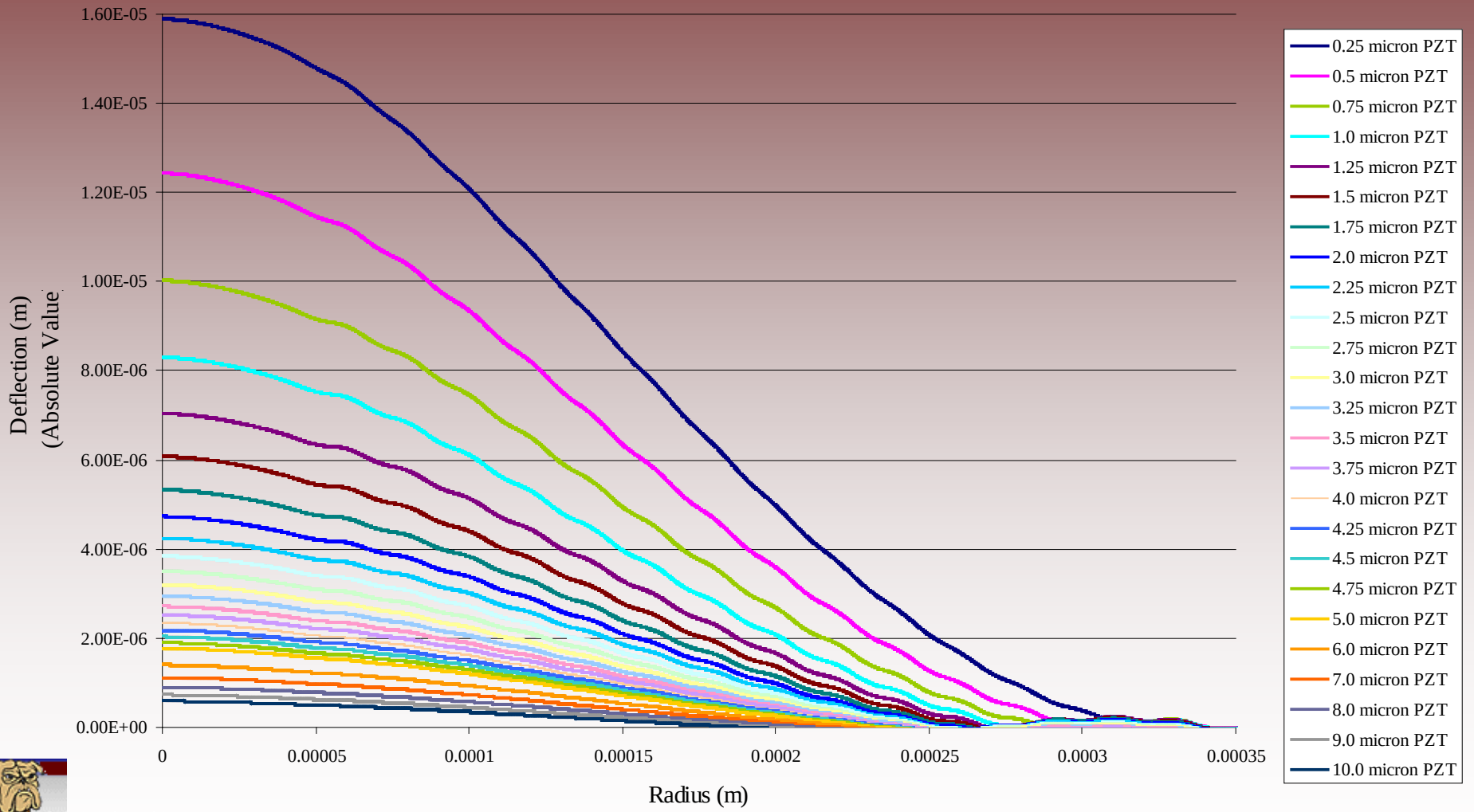
Piezoelectric MEMS Design Parametric Analysis

- Models normalized based on diaphragm diameter
  - Material thicknesses with an emphasis on piezoelectric thickness
  - Electrode width
  - Electrode separation
  - Center disk diameter



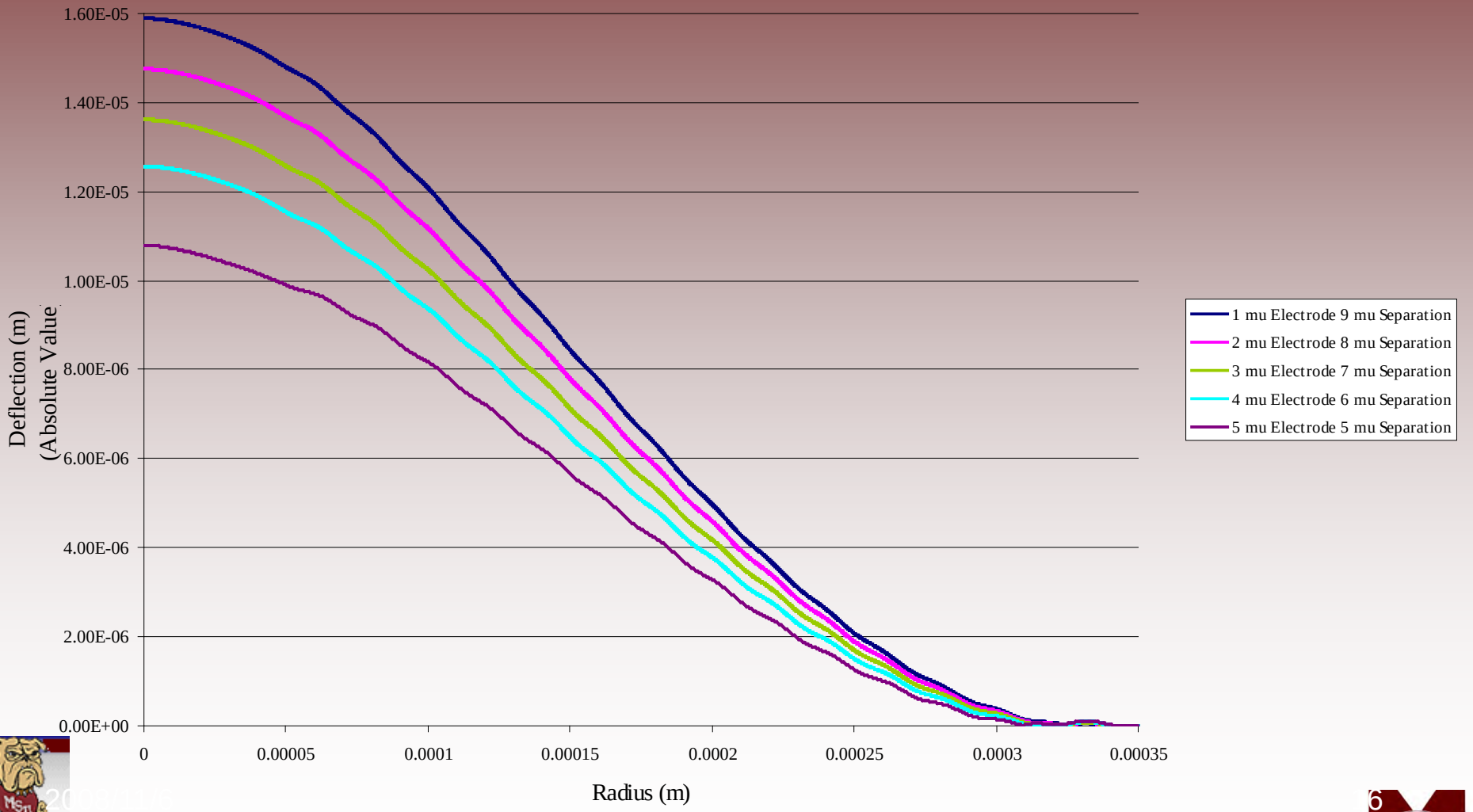
Design Optimization

Parametric Models - Deflection vs. PZT Thickness (1μm electrode width, 9 μm electrode pitch)

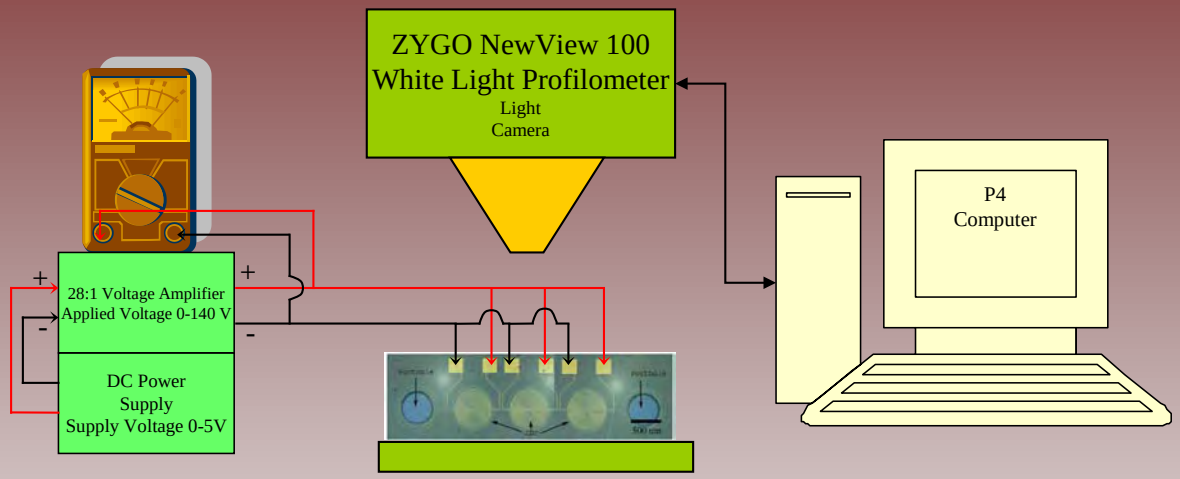


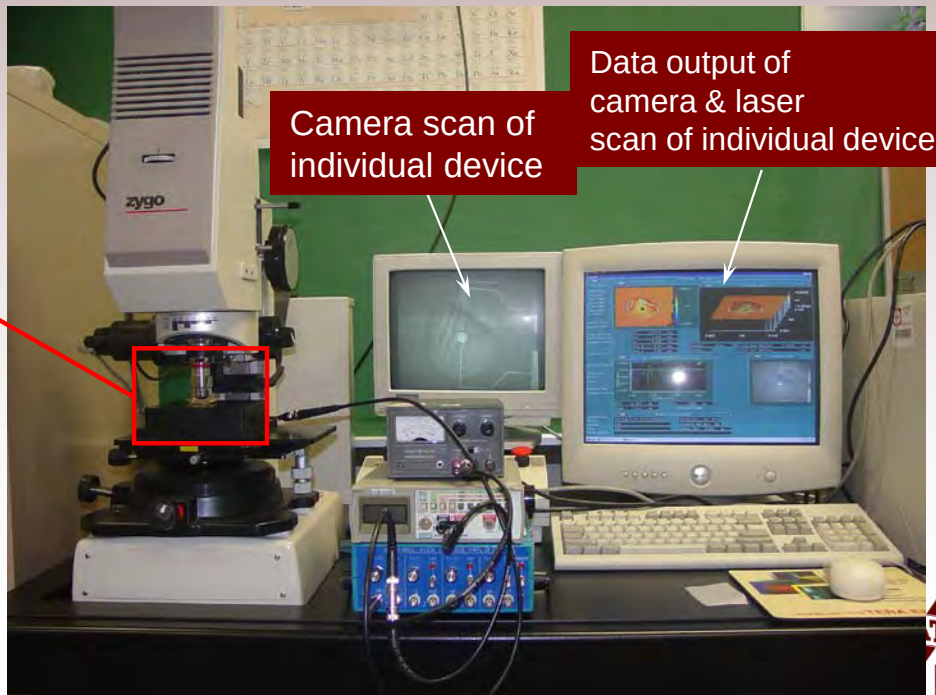
Design Optimization

Parametric Models - Deflection vs. PZT Thickness (0.25μm PZT, varying electrode width and pitch)

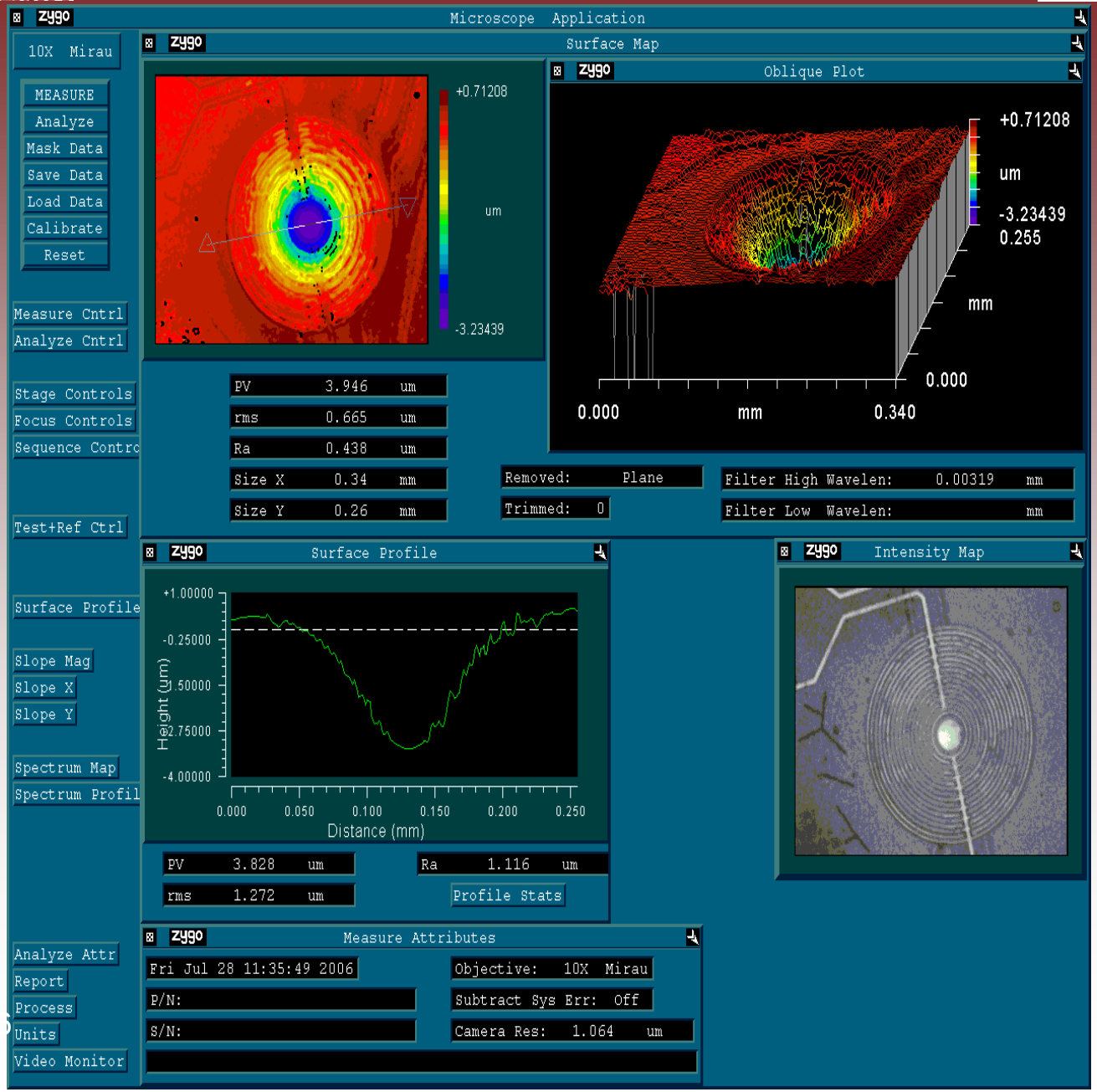


Experimentation – Static Deflection





Experimentation Static Deflection



Deflection vs. Polarity of Experimental Diaphragms

Diaphragm	Deflection (μm)	
	Positive Inside	Positive Outside
Actuator 1 Lot 4-4-1	Broken	
Actuator 2 Lot 4-4-1	3.49	2.52
Actuator 1 Lot 4-4-2	3.20	2.55
Actuator 2 Lot 4-4-2	3.40	3.49
Actuator 4 Lot 4-4-2	2.85	2.79
Actuator 4 Lot 4-4-3	2.93	2.90

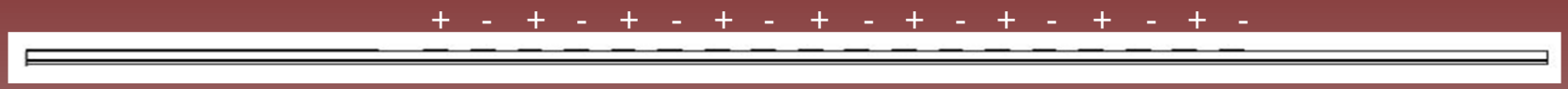
650 mm Diaphragm w/ 90 mm Center Disk

Note: Odd Number of Electrodes (21)

Residual Stresses (MPa)					
Voltage	ZrO_2	SiO_2	*PZT*	$\delta_{exp}\,(\mu m)$	$\delta_{sim}\,(\mu m)$
100	270	206	60	3.93	3.933
140	350	245	0	6.44	6.452
180	400	305	0	7.93	7.99

$\delta_{max\_exp180V} = 7.98\ \mu m$

650 µm Diaphragm w/ 150 mm Center Disk



Note: Even Number of Electrodes (18)

Residual Stresses (MPa)					
Voltage	ZrO_2	SiO_2	*PZT*	$\delta_{exp}\,(\mu m)$	$\delta_{sim}\,(\mu m)$
100	270	205	130	2.13	2.136
140	360	255	0	5.86	5.88
180	410	315	0	7.17	7.13

$\delta_{max\_exp180V} = 7.17\ \mu m$

650 mm Diaphragm w/ 210 mm Center Disk

Large Center Disk and 15 electrodes

Residual Stresses (MPa)					
Voltage	ZrO_2	SiO_2	*PZT*	$\delta_{exp}\,(\mu m)$	$\delta_{sim}\,(\mu m)$
100	29	29	0	1.44	1.435
140	30	35	30	1.45	1.424
180	0	0	30	1.41	1.415

$\delta_{max\_exp140V} = 1.45\ \mu m$

Conclusion

- Identify trends for critical design parameters
  - Piezoelectric thickness, electrode pitch & width, center disk diameter, voltage polarity, physical boundary conditions, number of electrodes
- Design optimization beginnings
- Showed the effects of design parameter(s) coupling/combinations on deflection
- Experiments verified the decreasing deflection trend with respect to center disk diameter
- Initial verification of the effect of even number of electrodes on deflection (closed circuit)
- Identified the difference in deflection with respect to polarity
- Combined numerical models with given experimental data for design optimization beginnings