Accuracy and Composability in NODAS

Gilbert Wong, Gerard Tse[1], Qi Jing[3], Tamal Mukherjee[1], Gary K. Fedder[1,2]

[1]*Department of Electrical and Computer Engineering and [2]The Robotics Institute*
Carnegie Mellon University
Pittsburgh, PA 15213-3890

[3]*Mentor Graphics Corporation*
San Jose, CA, USA

fedder,tamal,gcwong,ktse@ece.cmu.edu
http://www.ece.cmu.edu/~mems

Outline

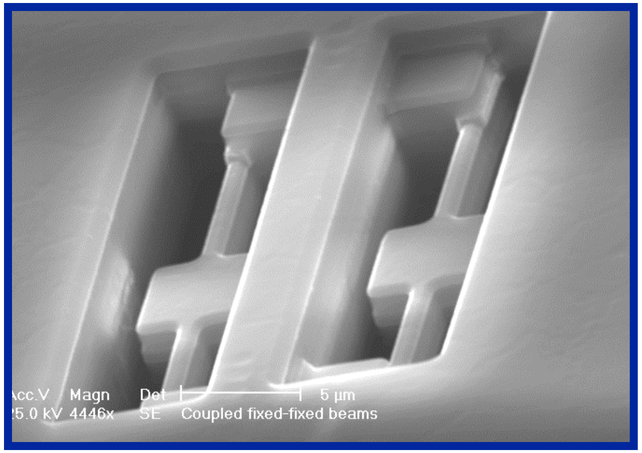
- Introduction
  - MEMS Simulation with NODAS
- Gap Model
  - Model Formulation
  - Contact Mechanism
  - Lateral Motion
- Accuracy and Composability
- Future Work

Introduction

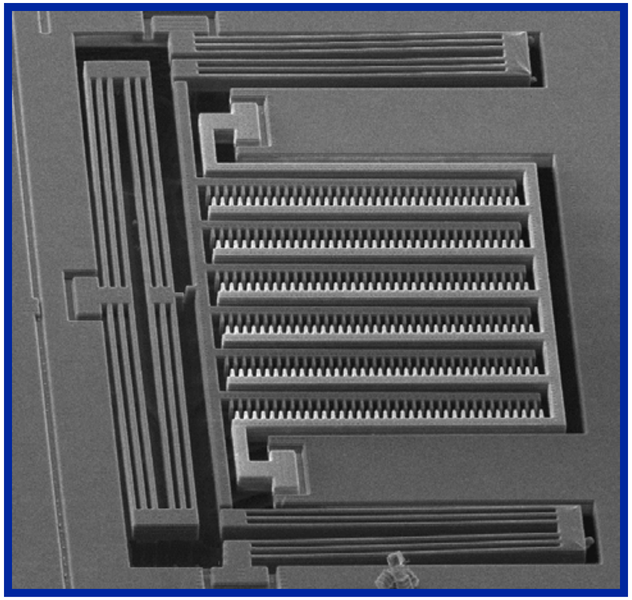
- NODAS (NOdal Design of Actuators and Sensors)
  - Library of composable MEMS atomic elements
    - Beams
    - Plates
    - Electrostatic Gaps
  - Simulation in Cadence Spectre
    - Electrical and mechanical co-simulation
- Examples of Related Work:
  - SUGAR, UC Berkeley
  - ARCHITECT, Coventor
  - Work by G. Lorenz and R. Nuel, Bosch

Composable MEMS Models

- Examples:
  - RF Switches
  - Resonant mixers/filters
  - Variable Capacitors
- Mechanical Models
  - Beams
  - Plates
- Electromechanical Model
  - Electrostatic Gaps



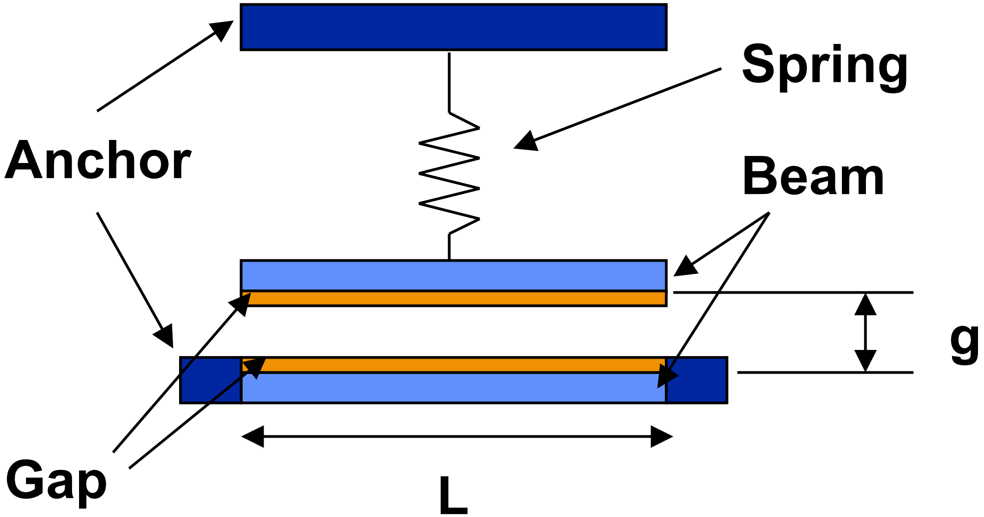
MEMS Resonant Mixer



MEMS Varactor

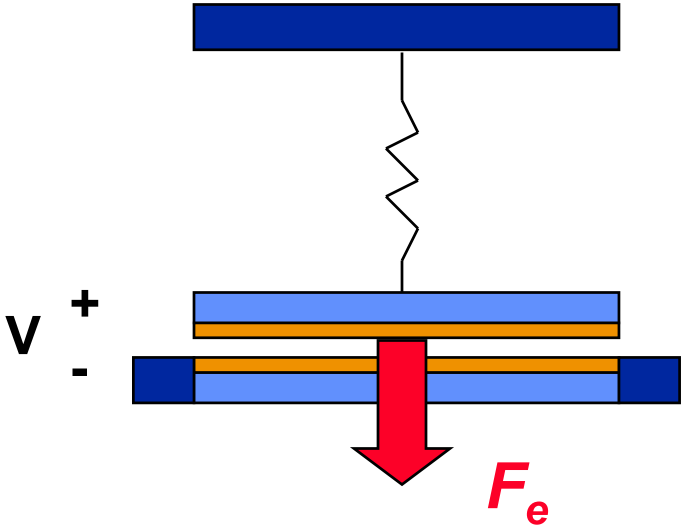
Canonical Problem

- Voltage across air gap
  - Generates electrostatic force
  - Displaces moveable electrode towards fixed electrode



Canonical Problem

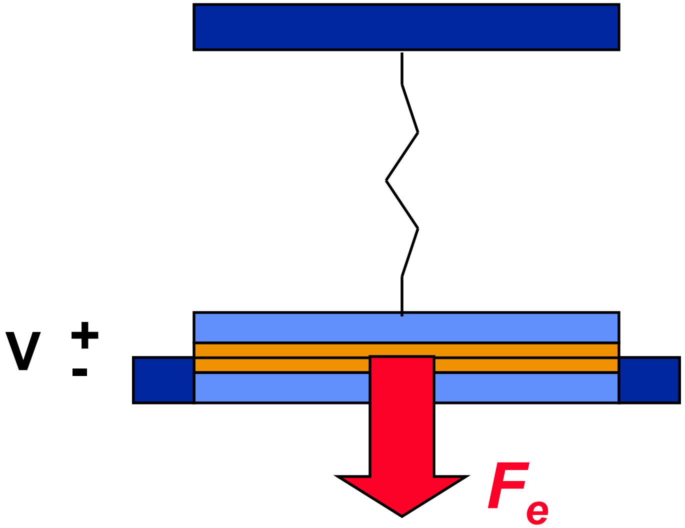
- Voltage across air gap
  - Generates electrostatic force
  - Displaces moveable electrode towards fixed electrode



$$F_e = \frac{1}{2}\frac{\varepsilon_o \cdot V^2 \cdot L \cdot T}{g^2}$$

Canonical Problem

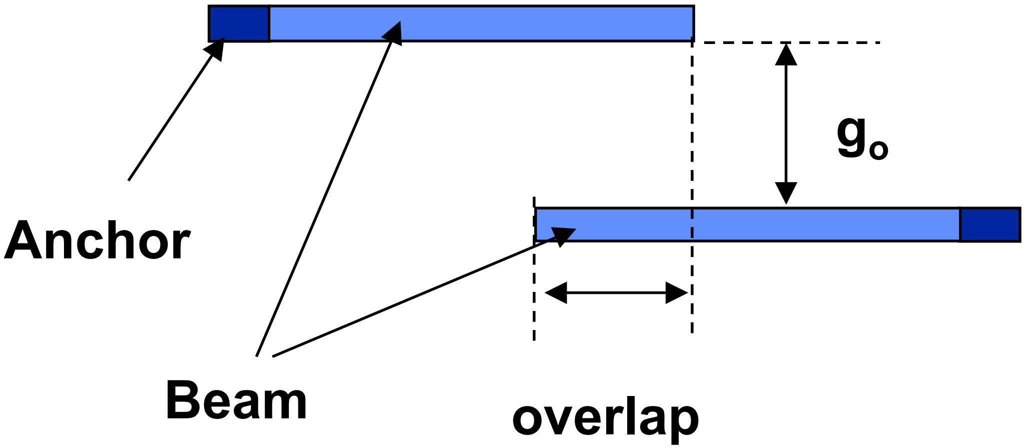
- Voltage across air gap
  - Generates electrostatic force
  - Displaces moveable electrode towards fixed electrode



$$F_e = \frac{1}{2}\frac{\varepsilon_o \cdot V^2 \cdot L \cdot T}{g^2}$$

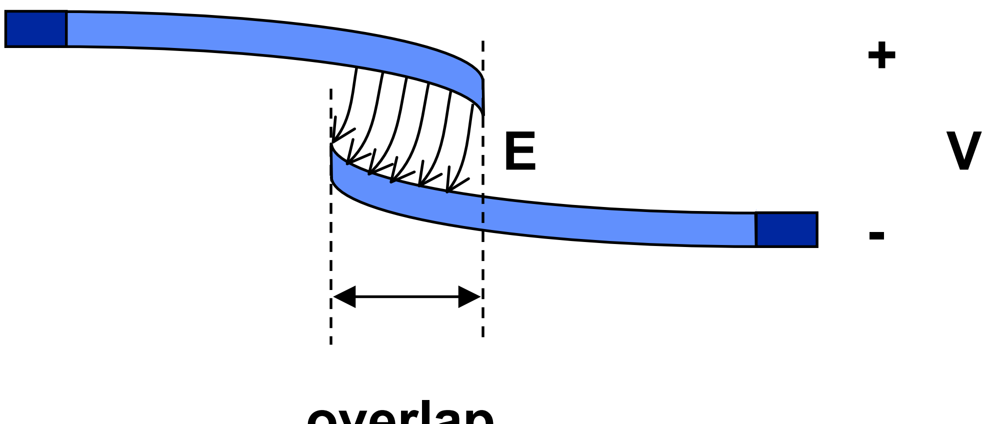
Model Formulation with Beam Electrodes

- Two cantilever beams separated by a gap g_o



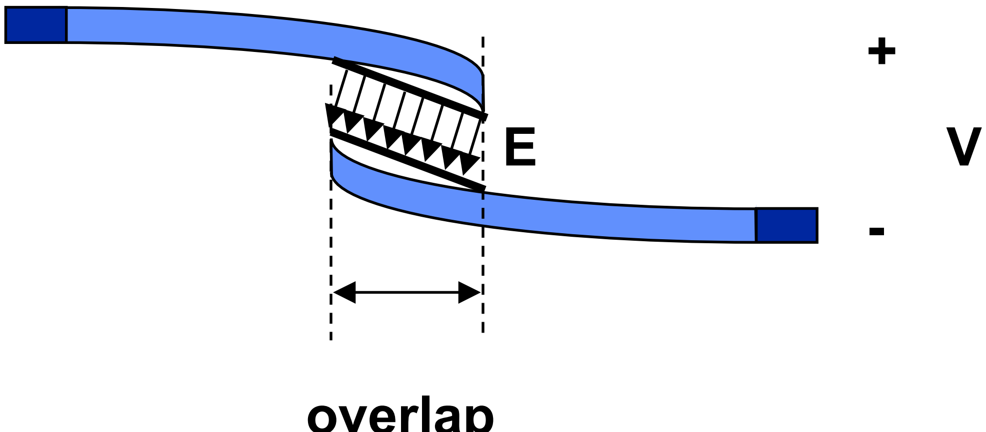
Model Formulation with Beam Electrodes

- Two cantilever beams separated by a gap g_o
- Apply voltage V:
  - Generates electric field E
  - Bends beams toward each other
- Difficult problem: no closed form solution



Model Formulation with Beam Electrodes

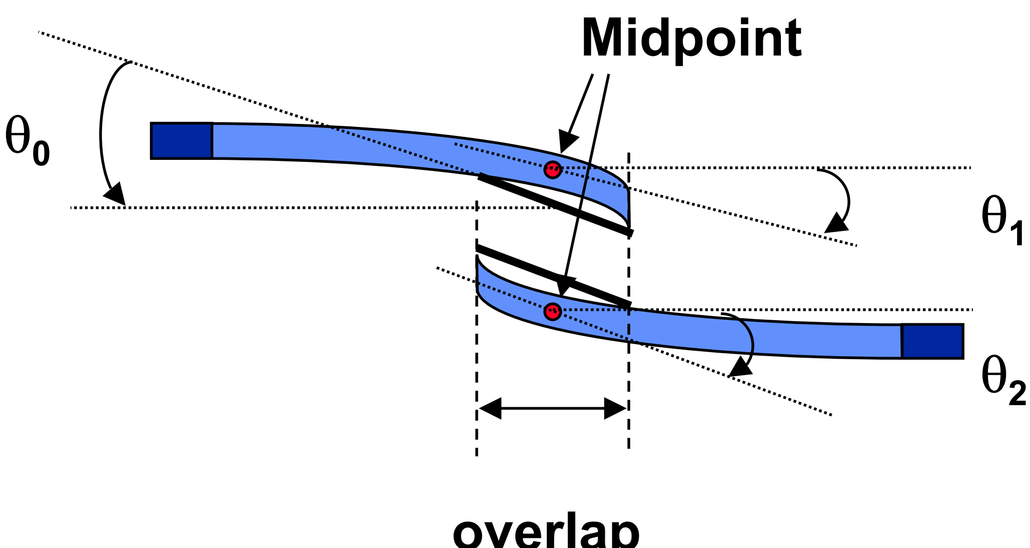
- Two cantilever beams separated by a gap g_o
- Apply voltage V:
  - Generates electric field E
  - Bends beams toward each other
- Difficult problem: no closed form solution
- **Approximate with rotated rigid parallel plates**



Rotated Parallel Plate

- Calculate rotation angle
  - Average angle at the midpoint of overlap region

```
theta0 = (ang1mid + ang2mid)/2.0;
```



$$\theta_o = \frac{\theta_1 + \theta_2}{2}$$

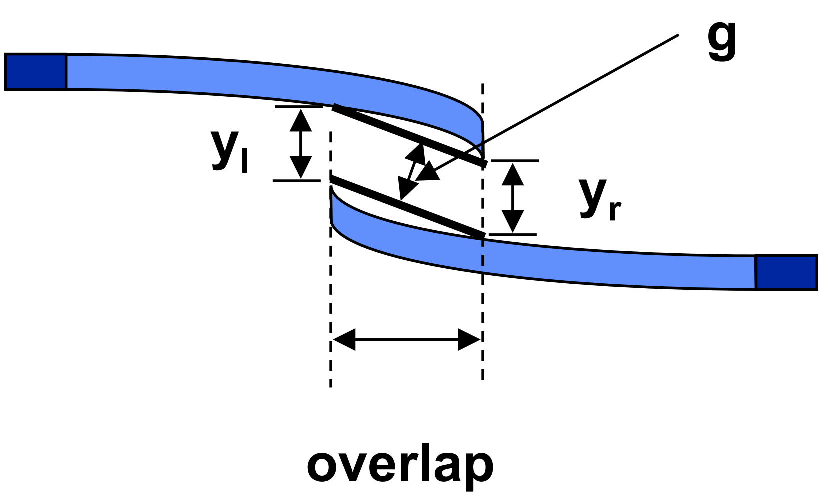
Rotated Parallel Plate

- Calculate rotation angle
  - Average angle at the midpoint of overlap region
- **Calculate gap**

$$g = \cos(\theta_o) * \min(y_l, y_r)$$

$$\texttt{dy\_l = min(}\overbrace{\texttt{(y1r-y2r+gap)}}^{y_r}\texttt{,}\overbrace{\texttt{(y1l-y2l+gap)}}^{y_l}\texttt{);}$$

```
dy = dy_l*cos(theta0);
```



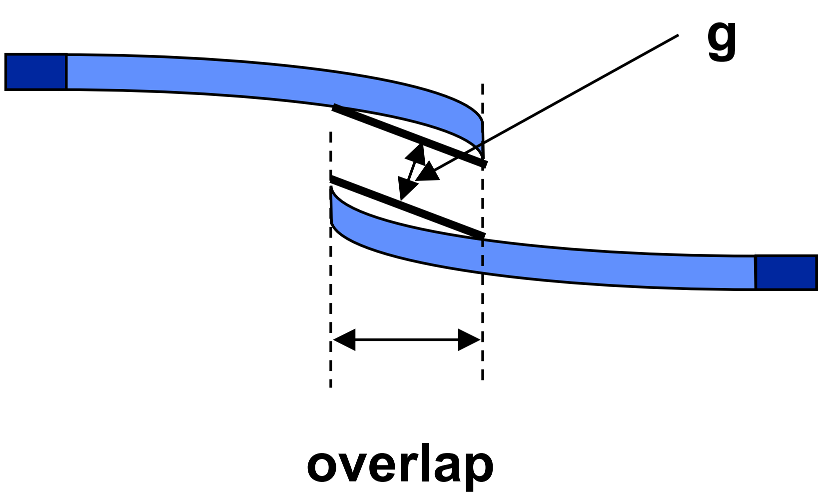
Rotated Parallel Plate

- Calculate rotation angle
  - Average angle at the midpoint of overlap region
- Calculate gap

$$g = \cos(\theta_o) * \min(y_l, y_r)$$

- **Calculate electrostatic force/length in this rotated frame**

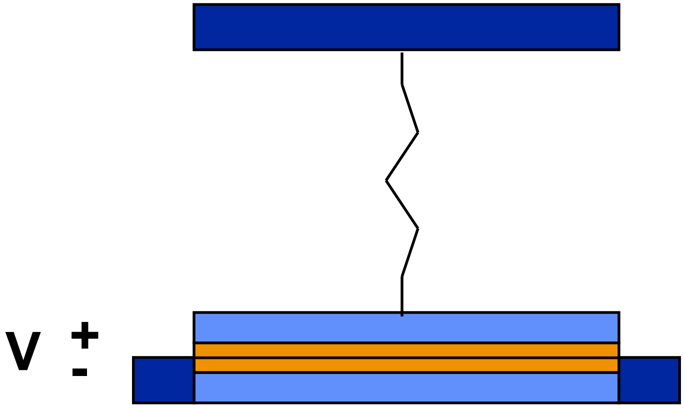
```
Felec=-0.5*`eps0*thickness*v_squared/pow(dy,2);
```



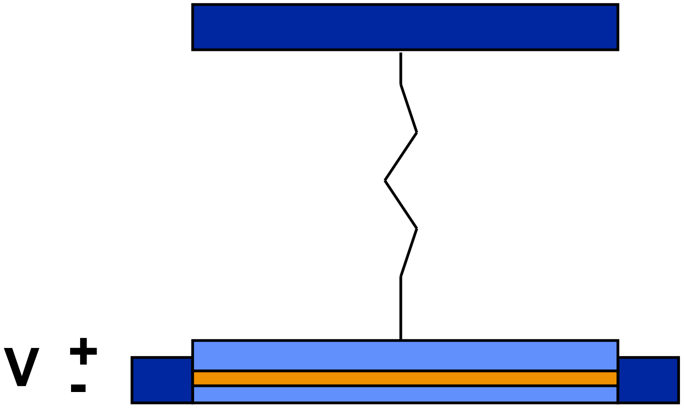
$$F_e = \frac{1}{2}\frac{\varepsilon_o \cdot V^2 \cdot overlap \cdot T}{g^2}$$

Contact Model

- Contact Model
  - Displacement beyond fixed electrode is non-physical (g < 0)
  - Contact force model prevents this



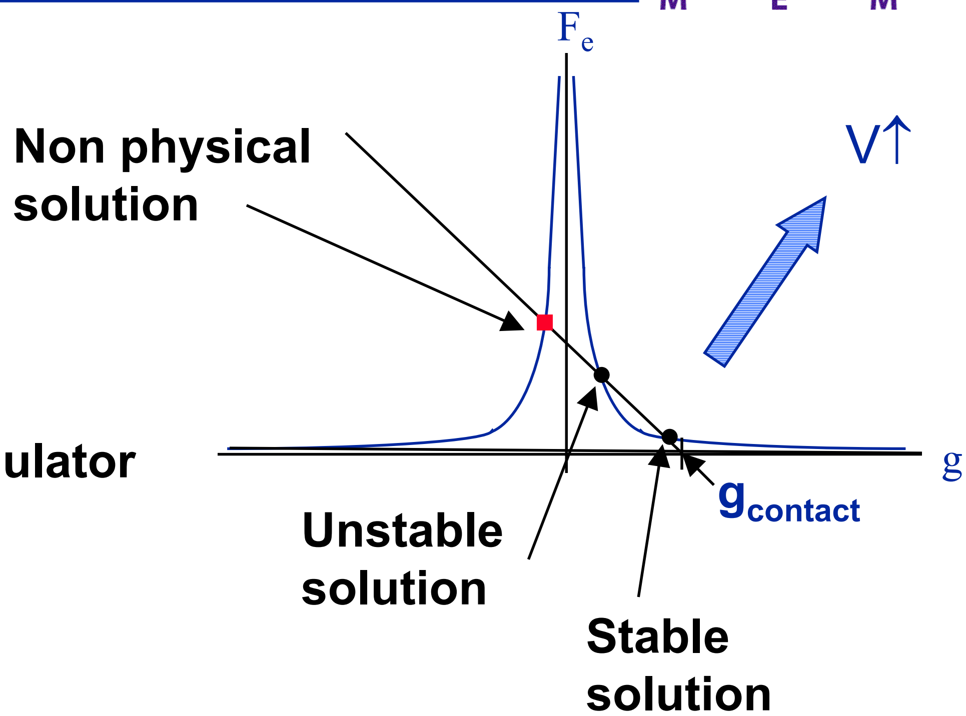
Beams in contact

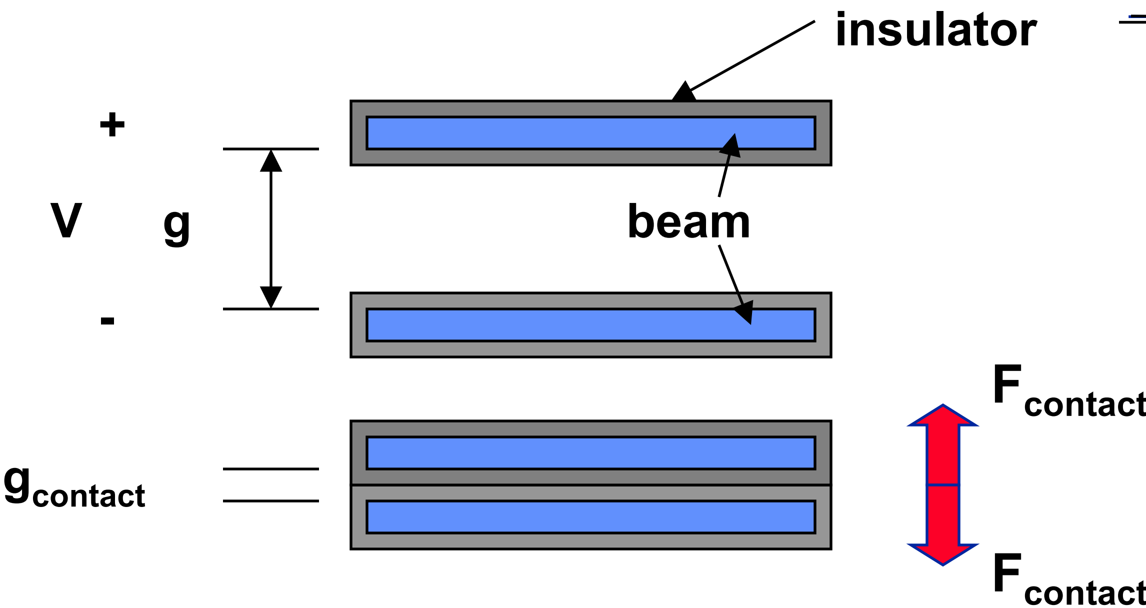


Non-physical solution

Gap Behavior in Contact

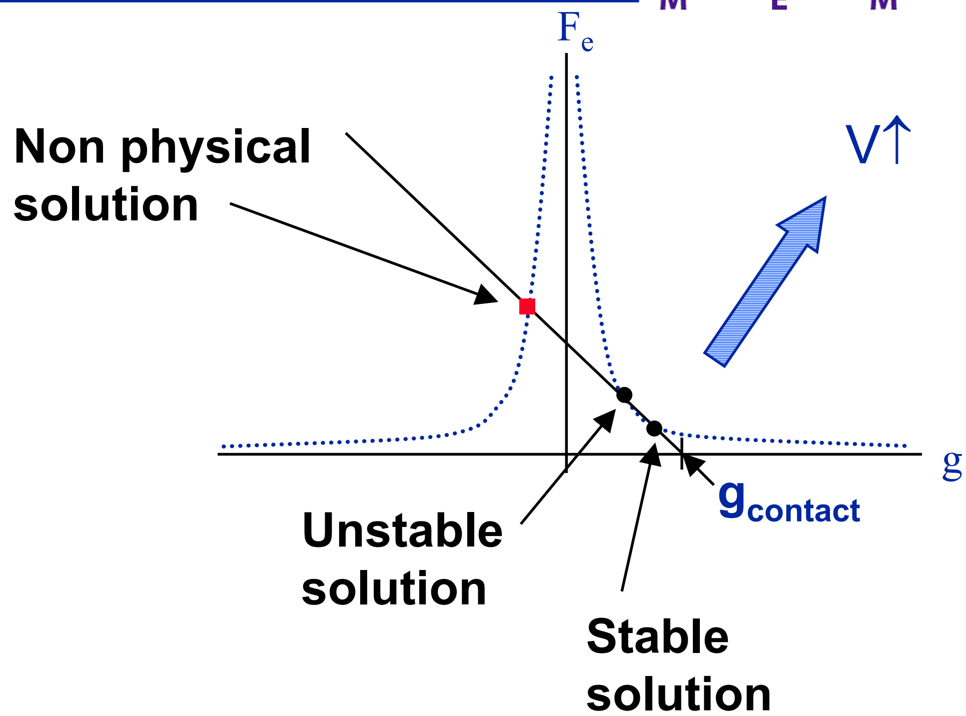
$$F_e = \frac{1}{2}\frac{\varepsilon_o \cdot V^2 \cdot L \cdot T}{g^2}$$

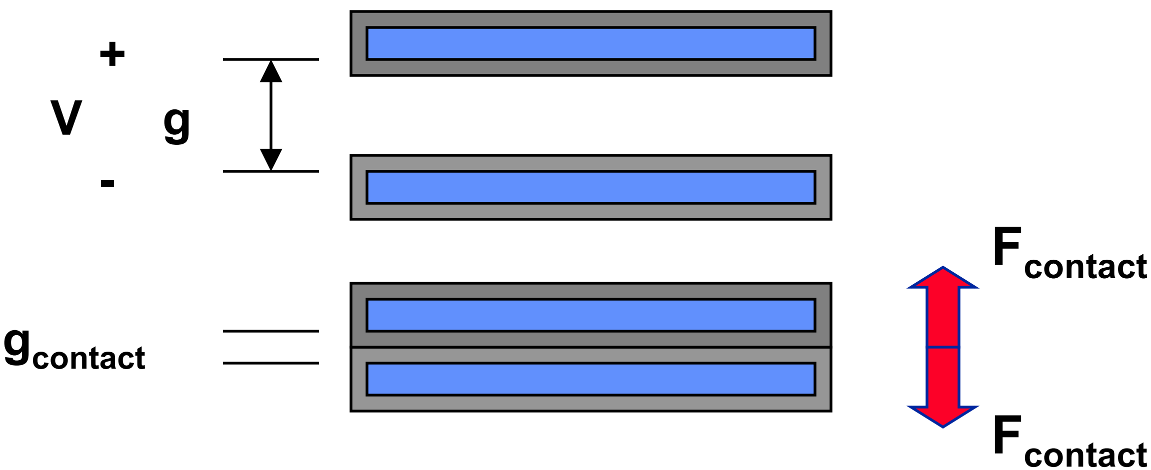




Gap Behavior in Contact

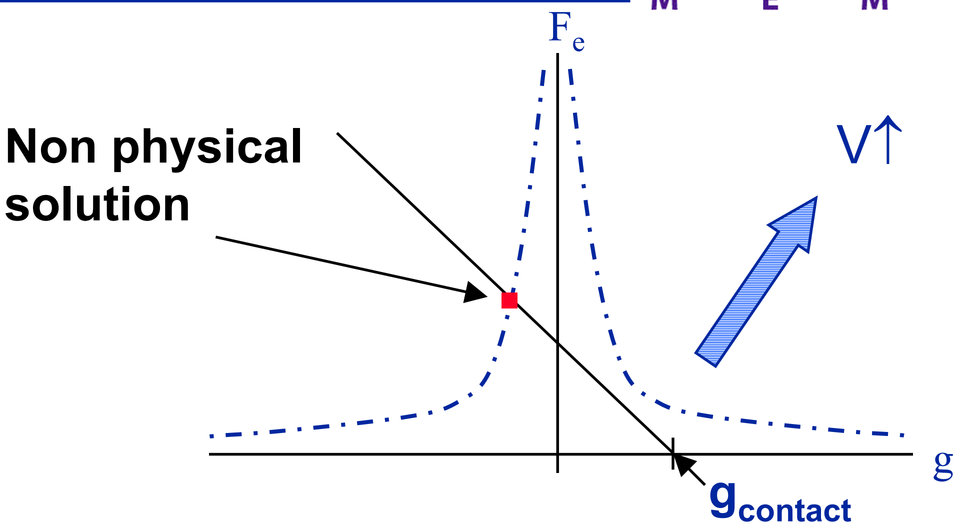
$$F_e = \frac{1}{2}\frac{\varepsilon_o \cdot V^2 \cdot L \cdot T}{g^2}$$

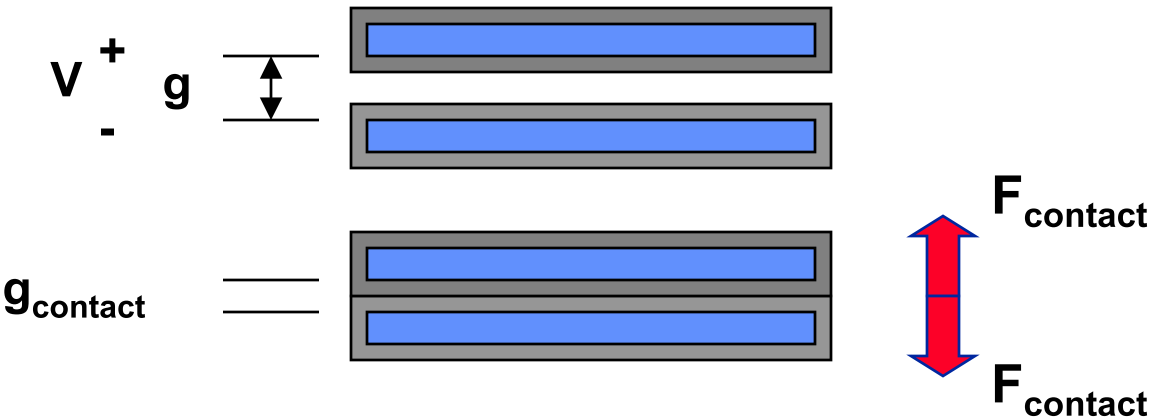




Gap Behavior in Contact

$$F_e = \frac{1}{2}\frac{\varepsilon_o \cdot V^2 \cdot L \cdot T}{g^2}$$

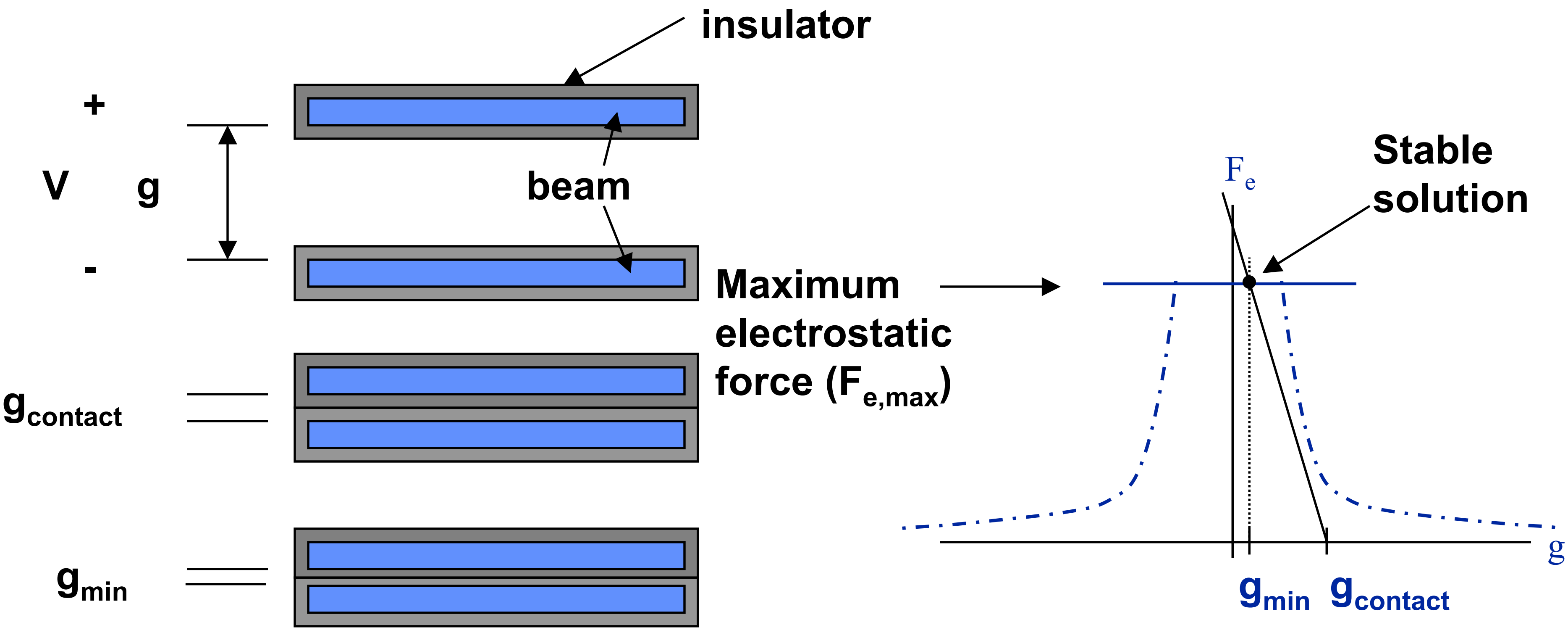




Gap Behavior in Contact

$$F_e = \frac{1}{2}\frac{\varepsilon_o \cdot V^2 \cdot L \cdot T}{g^2}$$

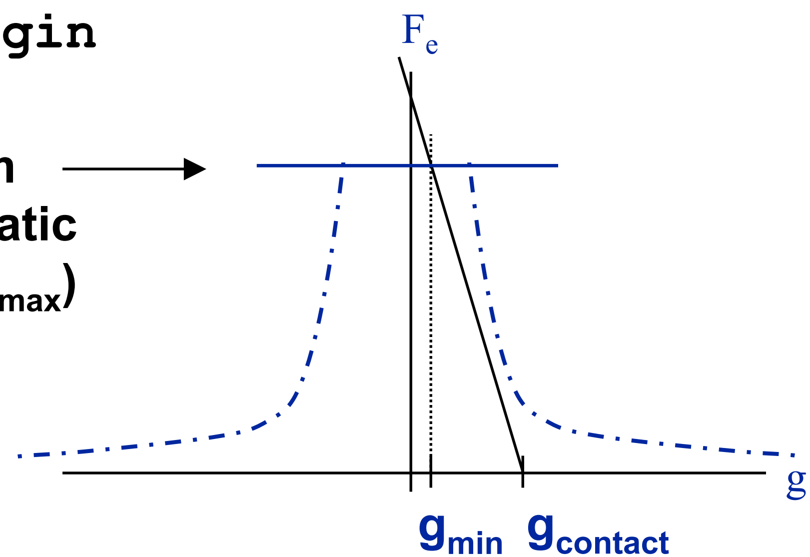
$$F_{e,max} = \frac{1}{2}\varepsilon_o \cdot \mathrm{E}_{BD}^2 \cdot L \cdot T$$



Contact Model Verilog-A

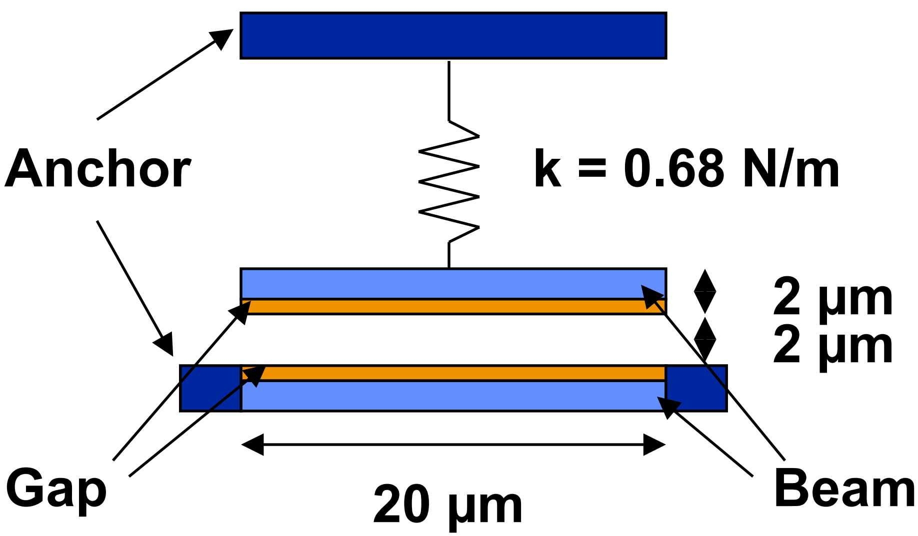
```
FeMax =  - 0.5*`eps0*thickness*pow(elec_breakdown,2);
slope = FeMax/(gmin - gcontact);
if (dy<gcontact) begin
    Fy_contact = slope*(dy-gcontact);
end
else begin
    Fy_contact = 0;
end
if (abs(Felec) > abs(FeMax)) begin
    Fl = FeMax;
end
else begin
    Fl = Felec;
end
```

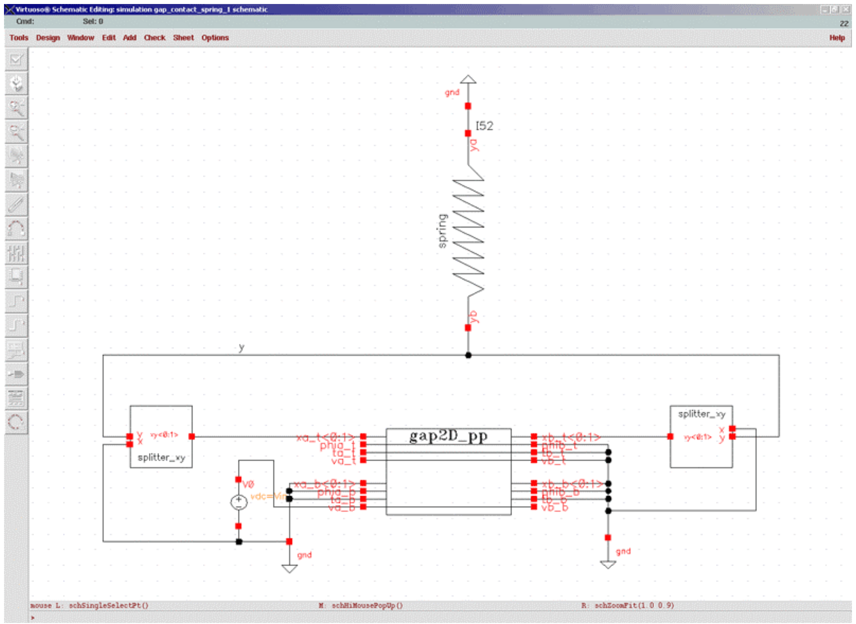
Maximum electrostatic force ($F_{e,max}$)



Verification Test Problem

- Use canonical problem
  - Check solutions from d.c. voltage sweep





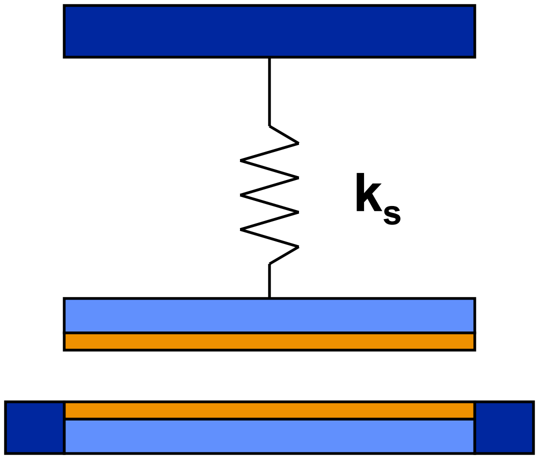
Snap In

- System unstable when $k_e > k_s$
- Gap snaps in at 2/3 of the original gap
- Pull in voltage, V_{PI} = 67.47 V for this case

$$F_e = \frac{1}{2}\frac{\varepsilon_o \cdot V^2 \cdot L \cdot T}{(g_o - y)^2} \qquad k_e = \frac{dF_e}{dy} = \frac{\varepsilon_o \cdot V^2 \cdot L \cdot T}{g^3}$$

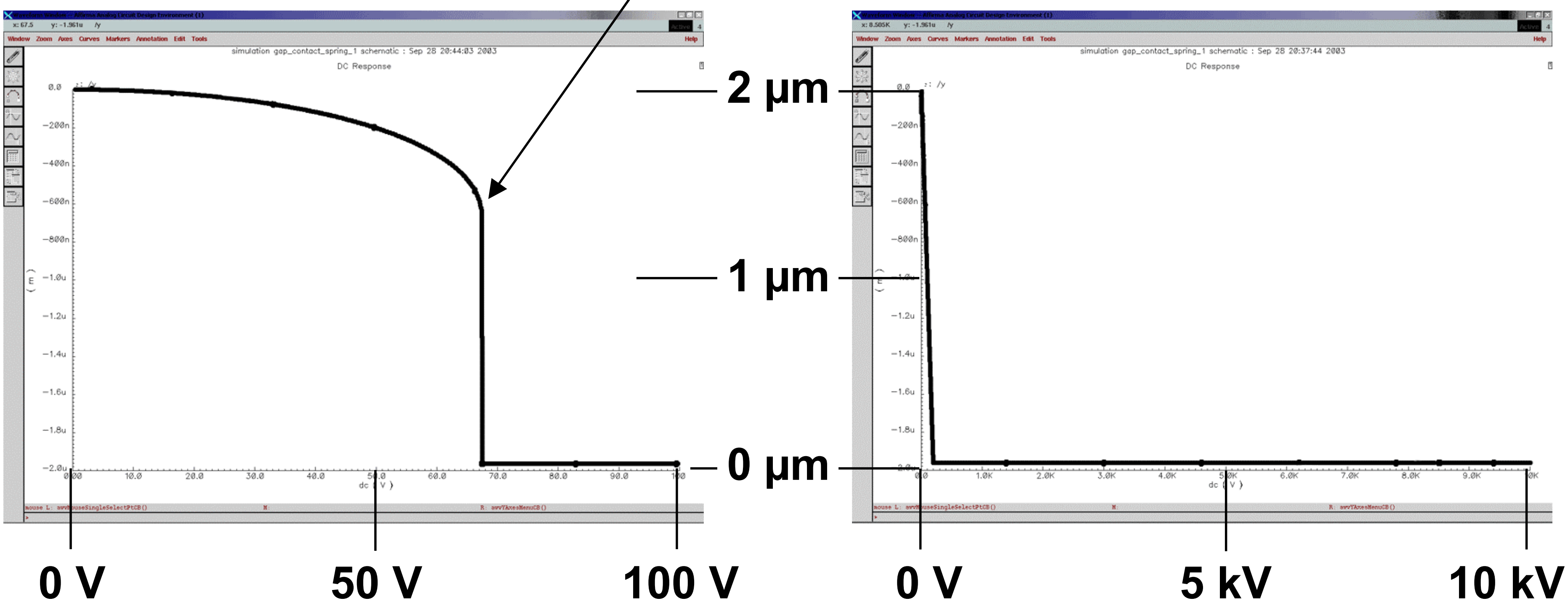
$$F_s = k_s \cdot y$$

$$g_{PI} = \frac{2}{3} g_o \qquad V_{PI} = \sqrt{\frac{k_s \cdot g_{PI}^3}{\varepsilon_o \cdot L \cdot T}}$$



Snap In/Contact Simulation

- Physical solution found
- Snap in occurs at V = 67.5 V

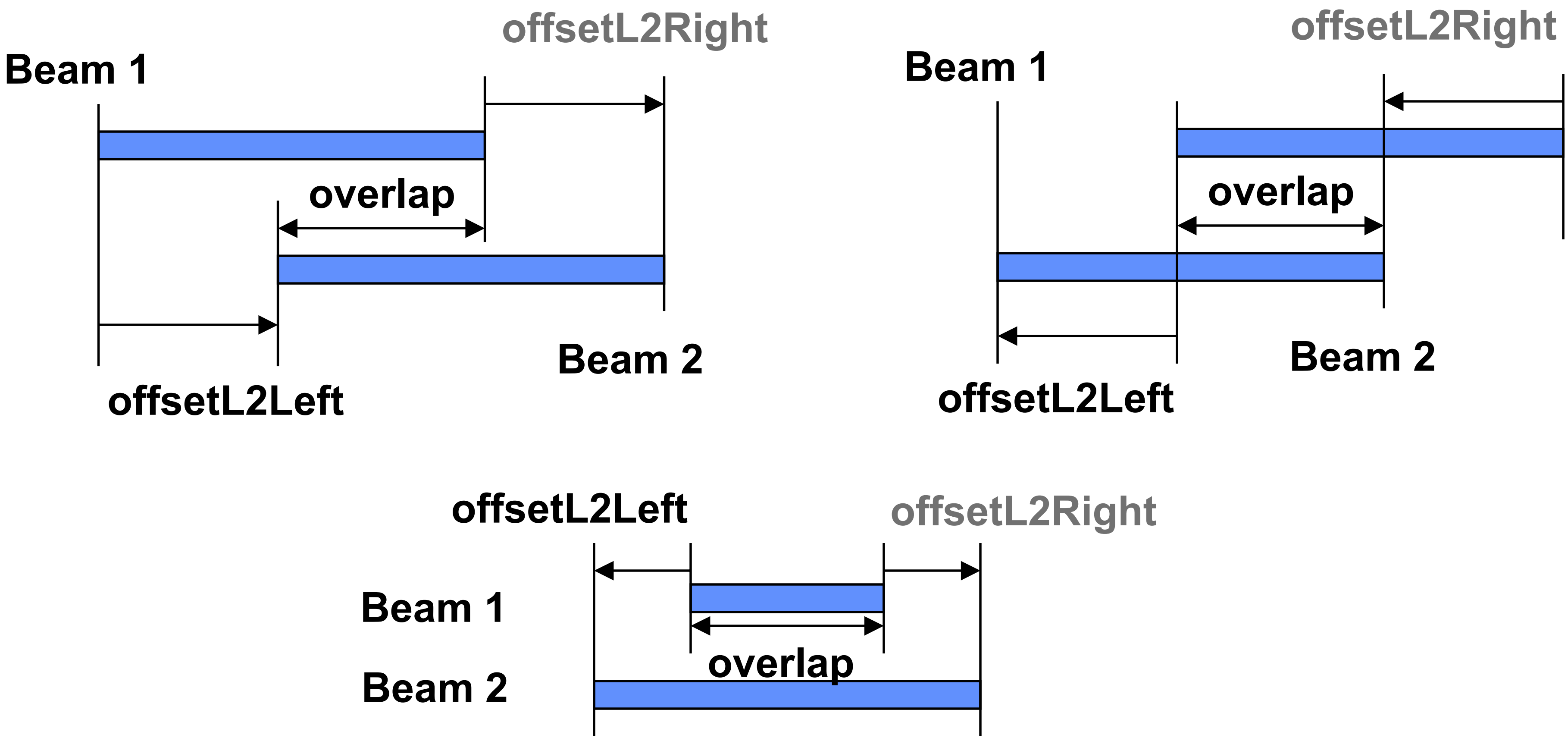


0 V - 100 V DC Sweep

0 V - 10000 V DC Sweep

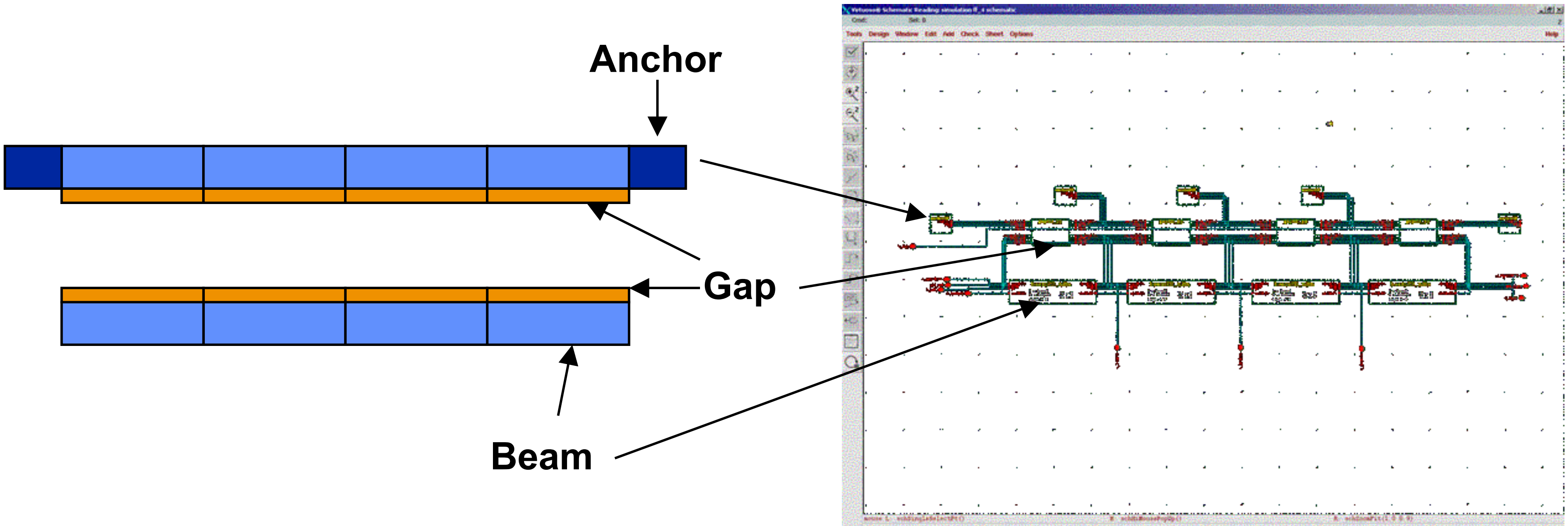
Lateral Motion

- Electrostatic force in x direction
  - Displaces electrodes laterally



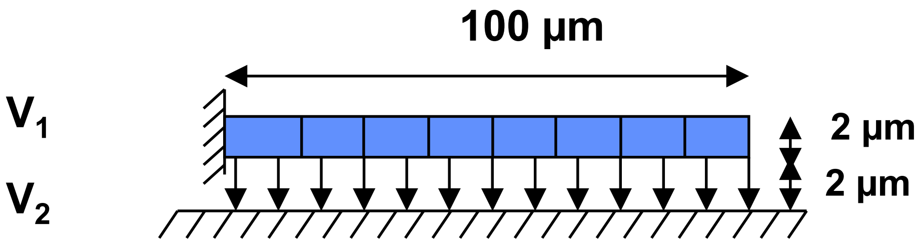
NODAS Composability

- NODAS model
  - Decompose beam into 2, 4, 8, 16, and 32 segments
- Verification: by comparison with FEMLAB



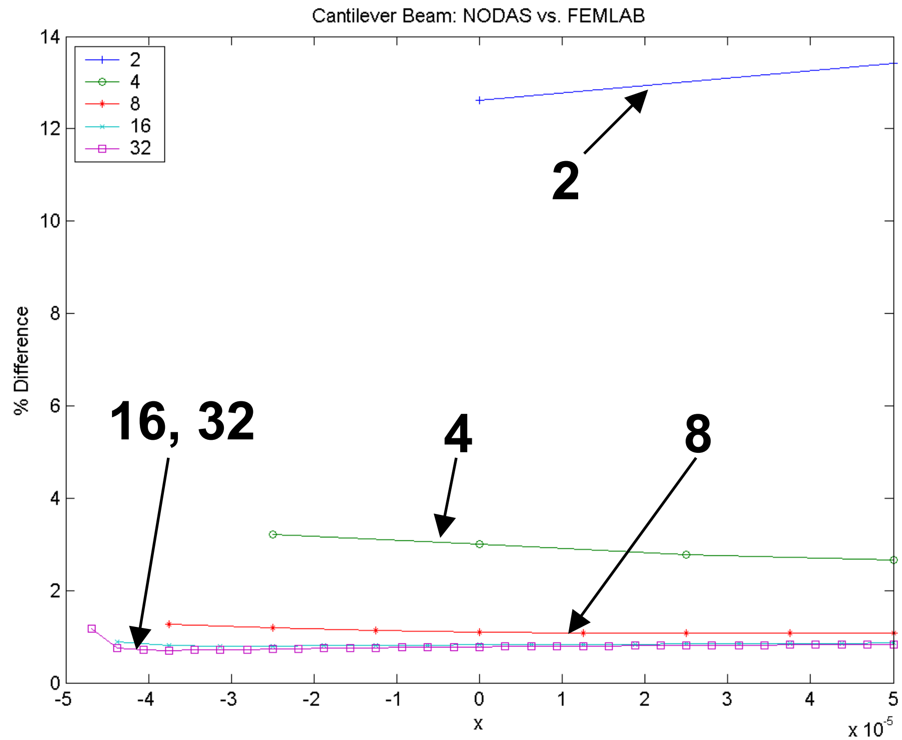
4 beam/gap segments **4 beam/gap segments schematic**

Electrostatically Actuated Cantilever

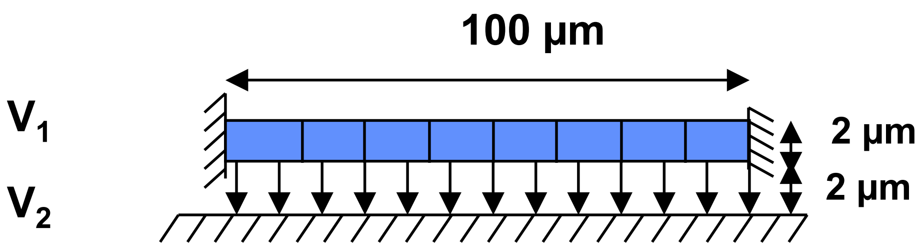


E = 170 GPa t = 2 µm
Density = 2330 kg/m^3

- Comparison between NODAS and FEMLAB
  - Large error for 2 segments
  - < 1% difference for ≥ 16 segments

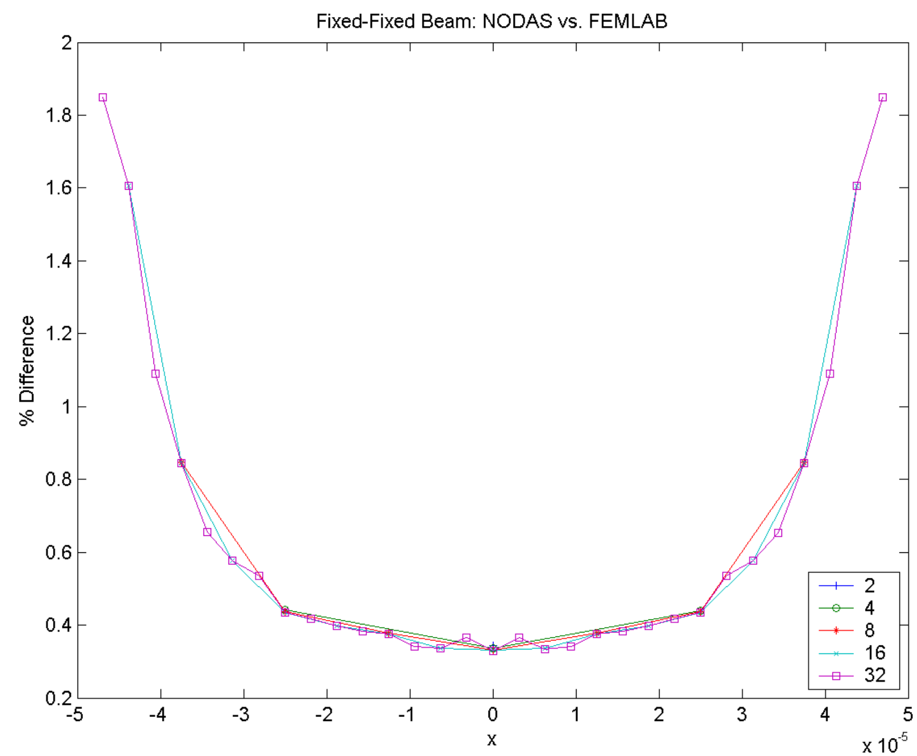


Electrostatically Actuated Fixed-Fixed Beam



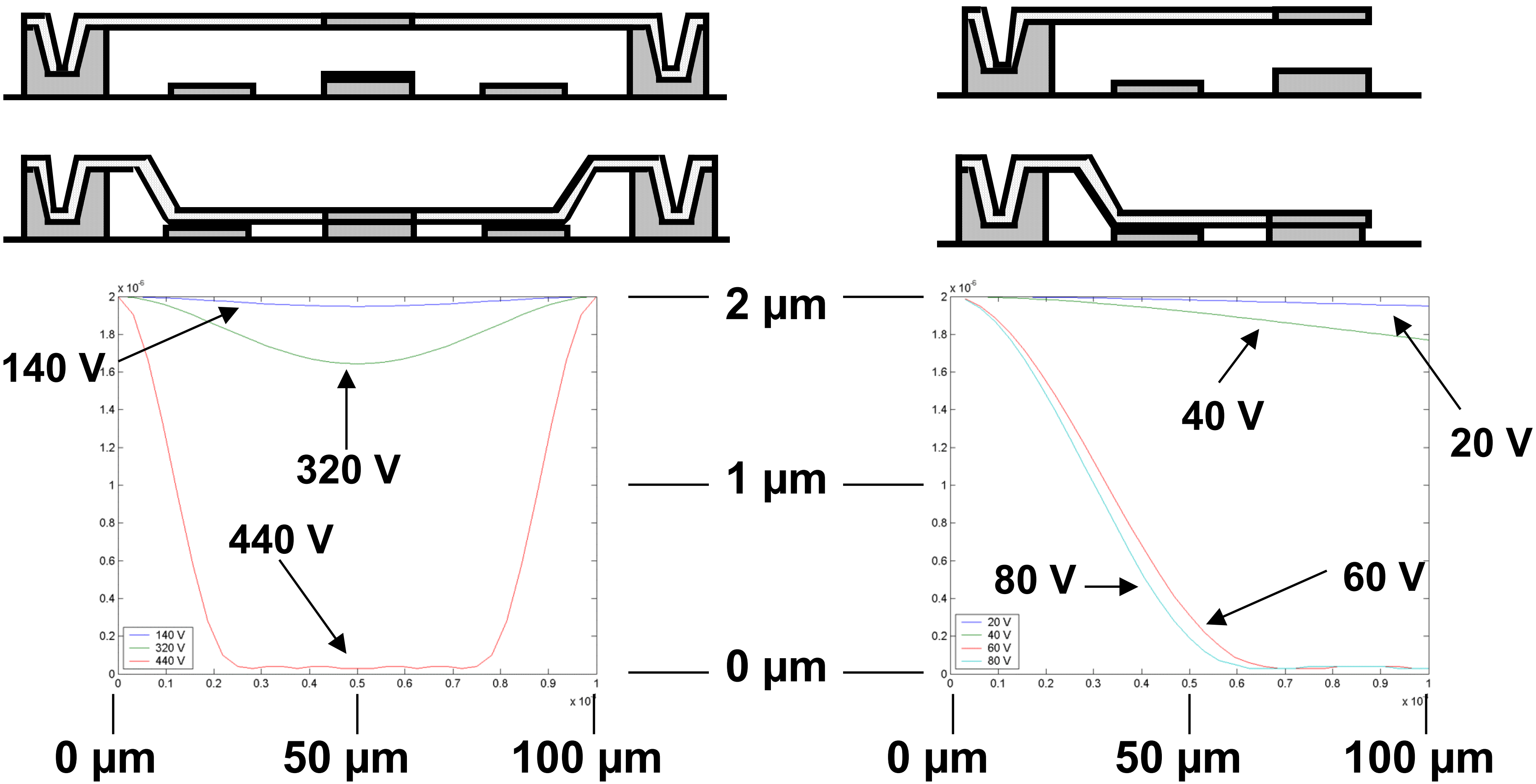
E = 170 GPa t = 2 µm
Density = 2330 kg/m^3

- Comparison between NODAS and FEMLAB
  - Error greatest at anchored ends (<1% if NODAS shear model used)
  - < 0.5% error at beam center



RF Switch Snap-In

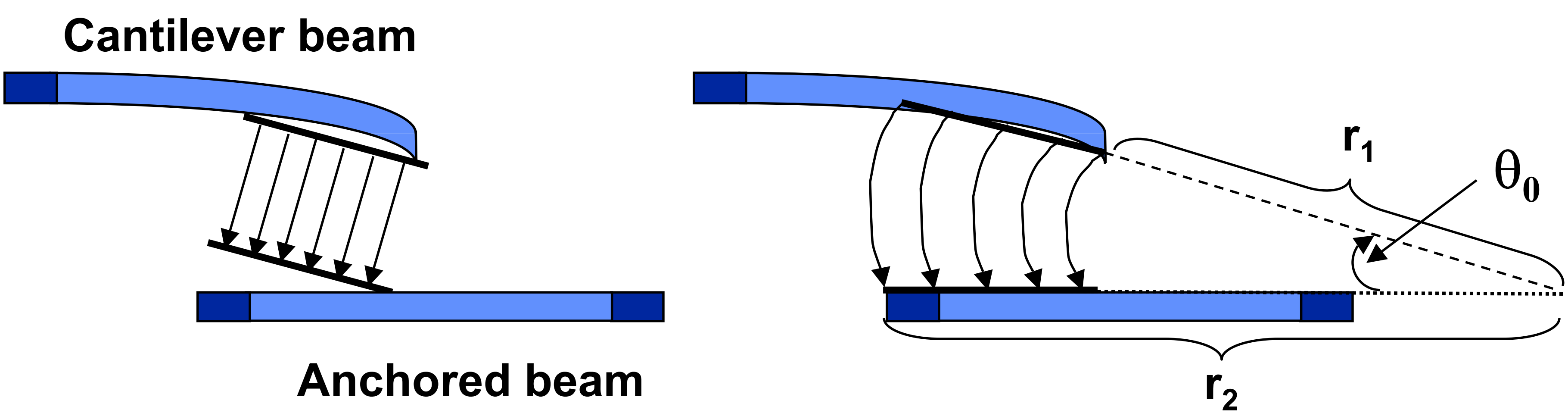
- 32 NODAS linear beam and gap elements



Beam Mode Shapes

Future Work

- Rotated parallel plate approximation
  - Valid when angles of beam electrodes match closely
  - Inaccurate when angle between beam electrodes different
- Use radial electric field between electrodes
- A-priori analytically integrate Taylor Series model of F_e



Acknowledgements

- DARPA and US Army CECOM
- Pittsburgh Digital Greenhouse