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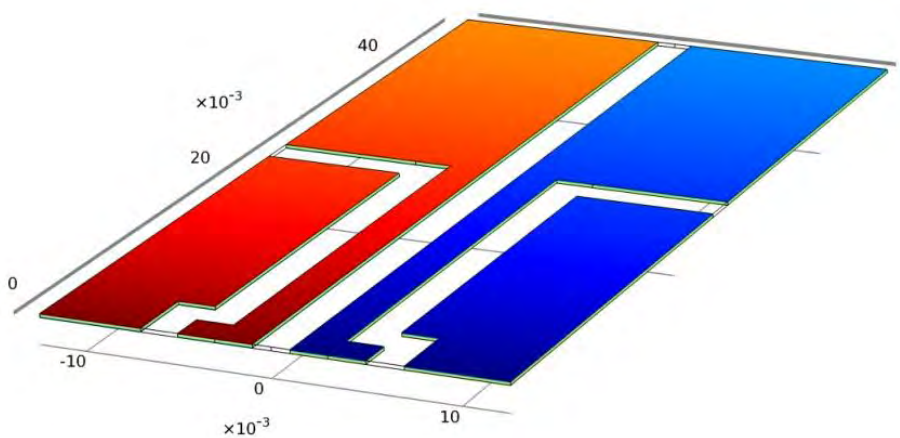
Advanced multi-physics actuation model of ionic polymer-metal composites



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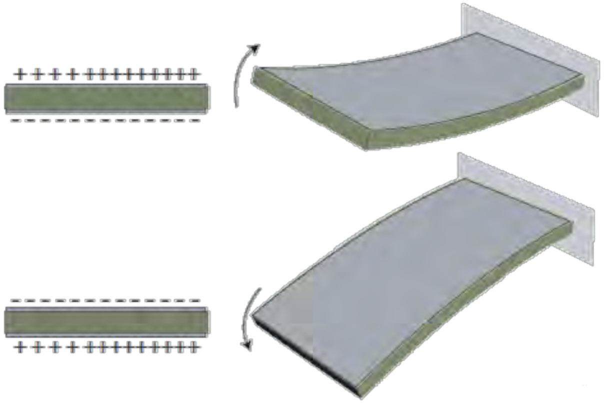
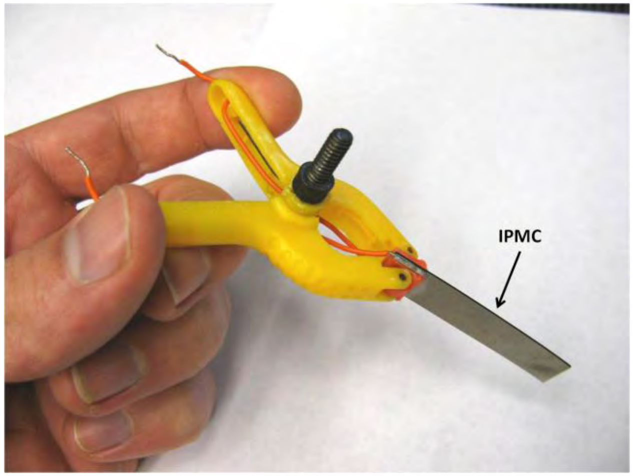
Outline

- **Ionic polymer-metal composite (IPMC) materials**
  - Working principle
  - Actuation model
- **Model implementation**
  - 2D model with electrode effect
    - Projection coupling to implement Ramo-Shockley theorem
  - 3D model
    - using couplings to overcome the high aspect ratio
  - Results

IPMC – working principle

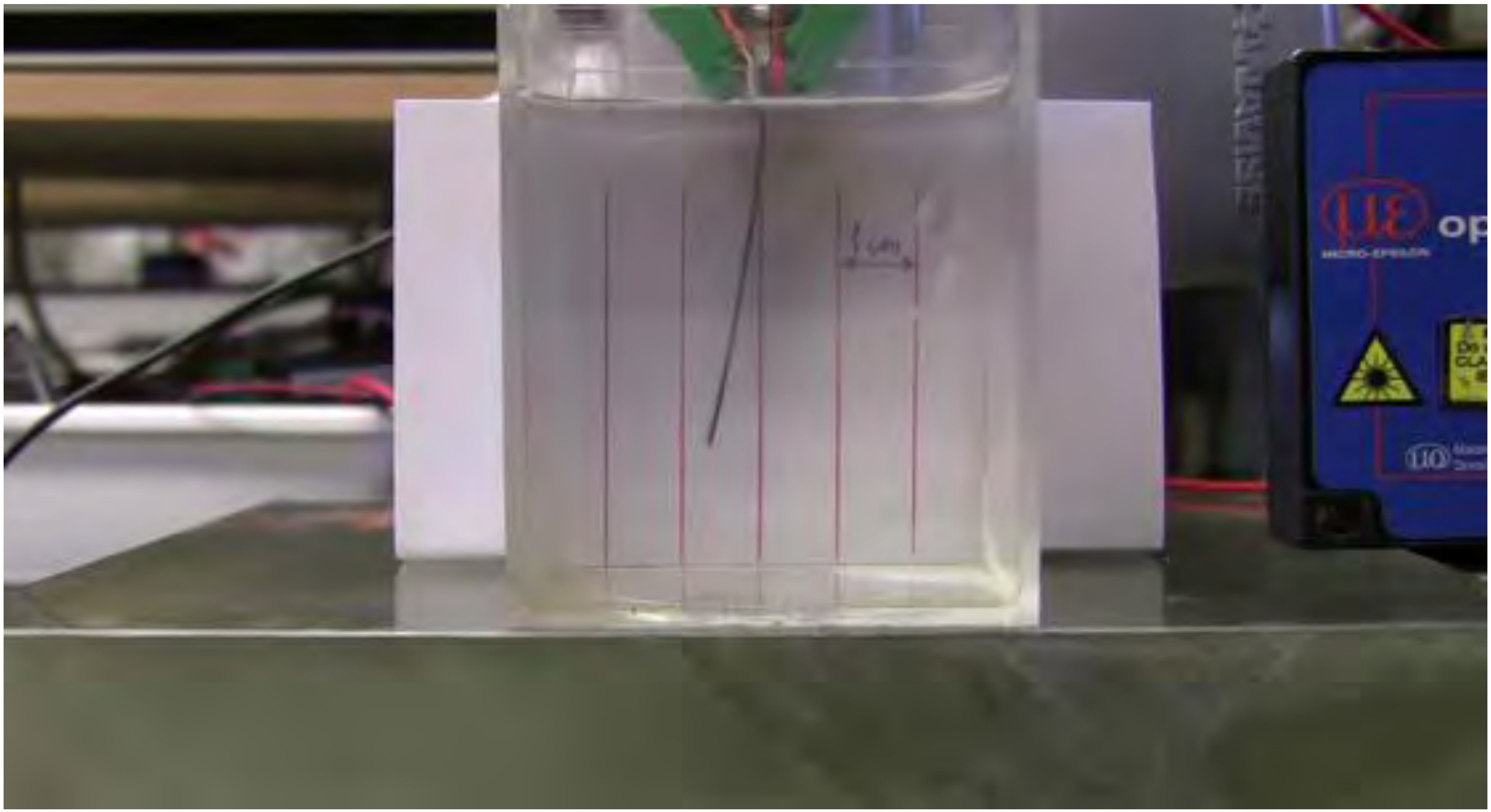
- **Thin polymer sheet sandwiched between noble metal electrodes**
  - Typically Nafion polymer with Pt electrodes
- **Applying a low voltage (1…4 V) results in significant bending of the material**
- **Benefits of using as an actuator**
  - Low voltage operation
  - Operates in wet environment
  - Noiseless





IPMC – working principle

- **Video: 0.5 mm thick, 5cm long, 3V AC**



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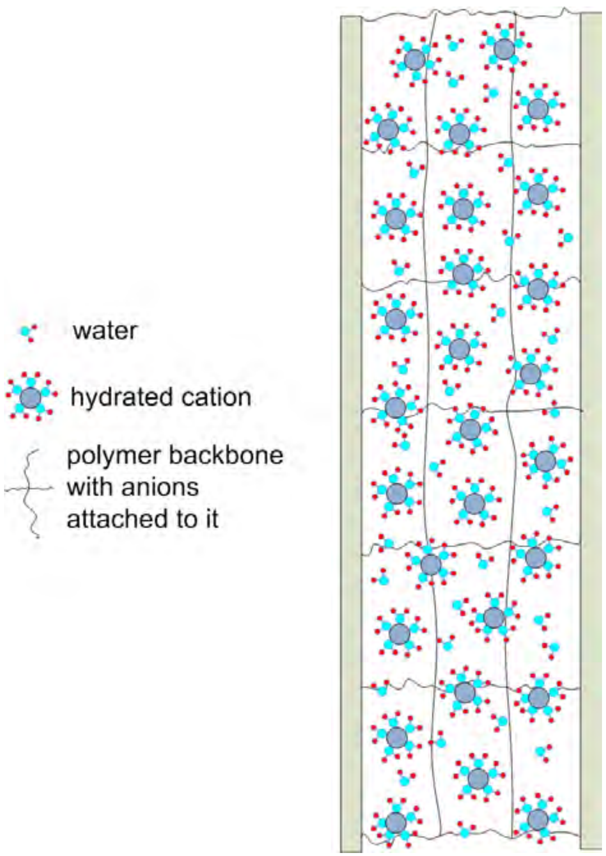
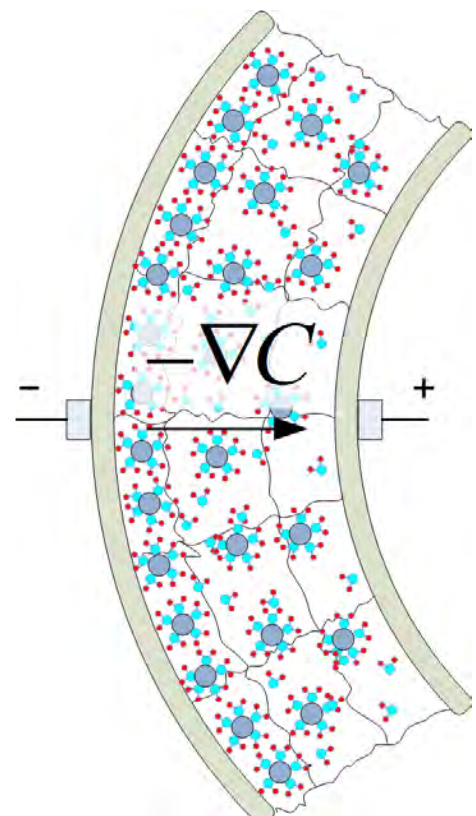
IPMC - Actuation model

- **Basic actuation model**
  - Cation accumulation / depletion causes body force → bending

voltage → cation concentration gradient





IPMC - 2D modeling

- **Governing equations**
  - Ionic currents
  - Electric currents
  - Navier's equation

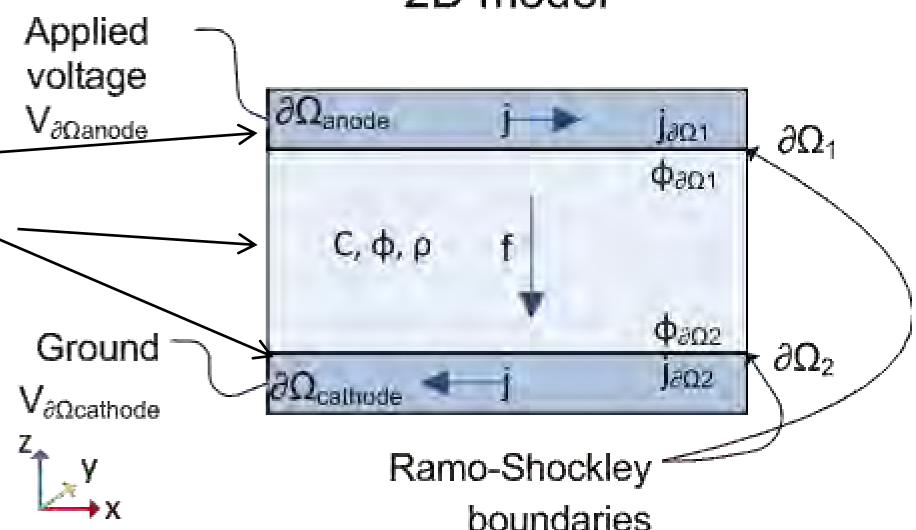
$$(\lambda + \mu)\, u_{k,ki} + \mu u_{i,jj} + F_i = 0$$

$$F_x = A\rho + B\rho^2, \quad F_y = 0$$

$$\frac{\partial C}{\partial t} + \nabla \cdot \left(-D\nabla C - z\mu F C \nabla \phi\right) = 0$$

$$-\nabla^2 \phi = \frac{F\,(C - C_0)}{\varepsilon}$$

2D model



$$\sigma \nabla V = -\vec{j}$$

$$j = \frac{1}{h} \int f\, dl$$

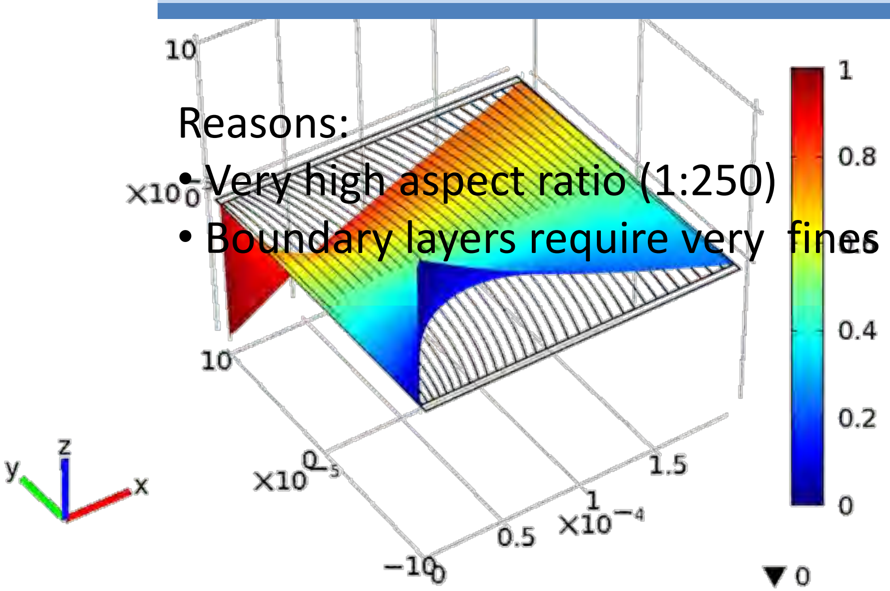
Projection coupling is used to relate ionic flux f to current density j

IPMC – 2D modeling

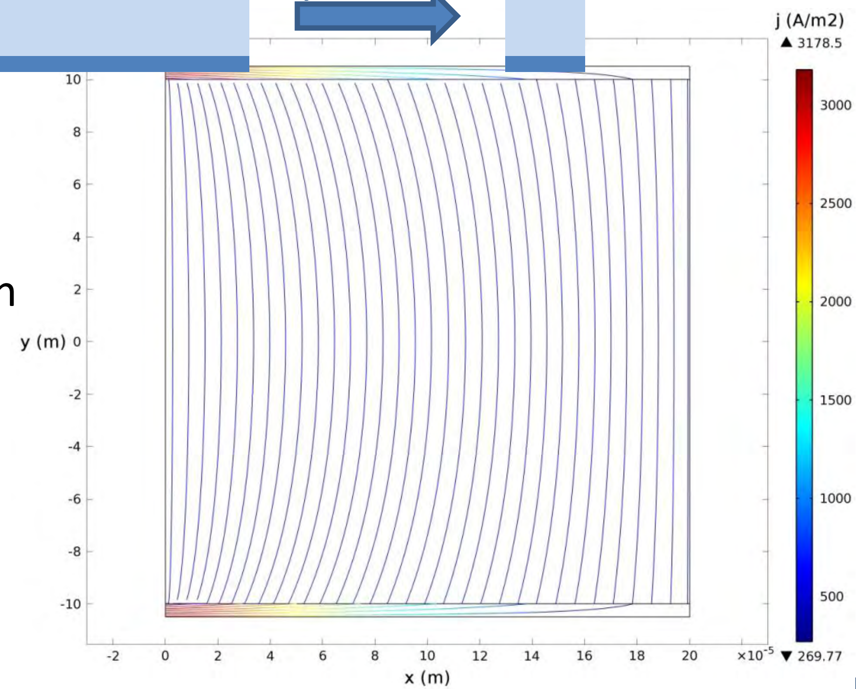
- **2D Comsol implementation**
  - Scale physical domain in longitudinal direction
  - Calculate the ionic and electric current part of the model

Voltage (magnitude and grad_x) and

Current streamlines in the electrodes polymer



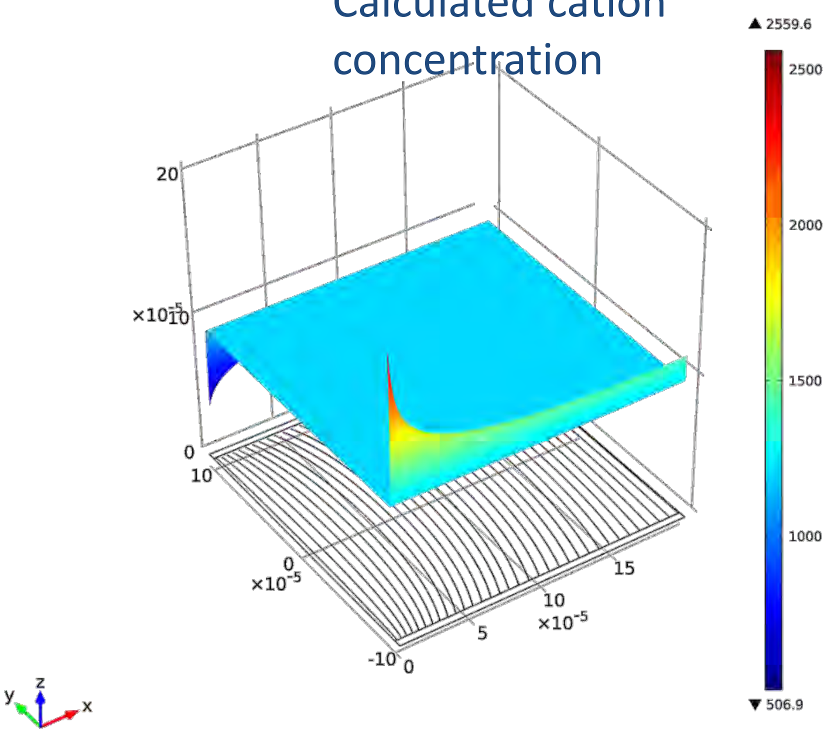
Reasons:
- Very high aspect ratio (1:250)
- Boundary layers require very fines mesh



IPMC – 2D modeling

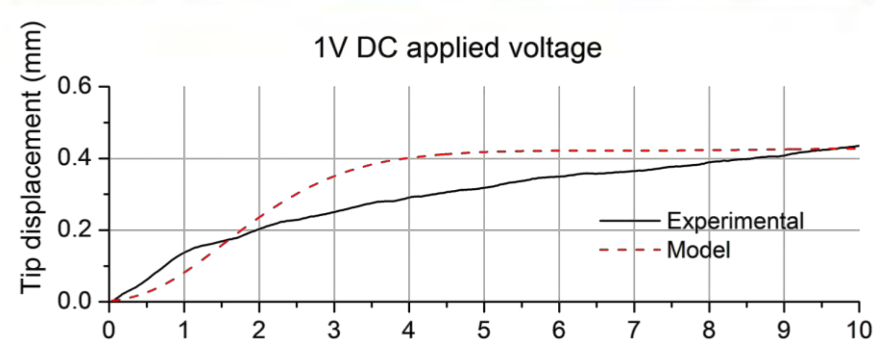
- **2D Comsol implementation**
  - Actuation is calculated on a full-scale domain
  - Cation concentration (or charge density) is projected from the scaled domain

Calculated cation concentration



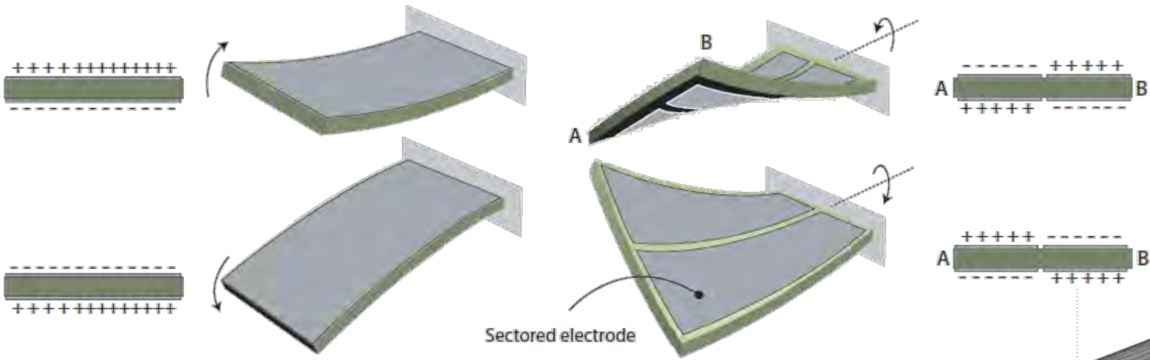
Cation concentration is projected on a full scale domain to calculate deformation

Rather coarse mesh is used



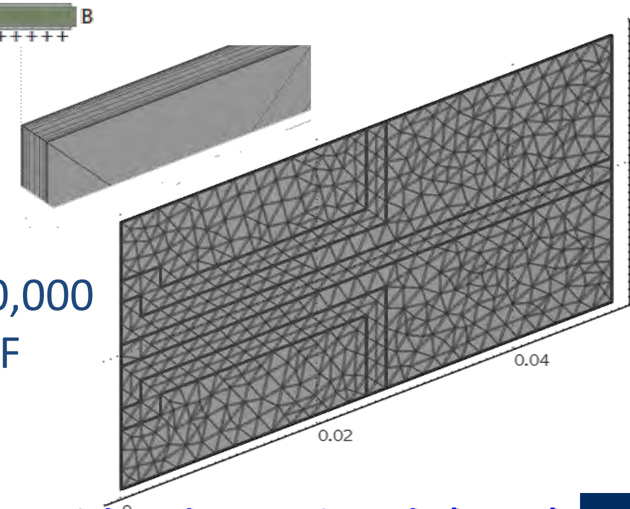
IPMCs for twisting actuation

- **Multi-DOF IPMCs**
  - Control surfaces for complex motion (fish fin)
  - Propulsion, maneuvering
  - Patterned IPMCs can be use to get multi-DOF actuation



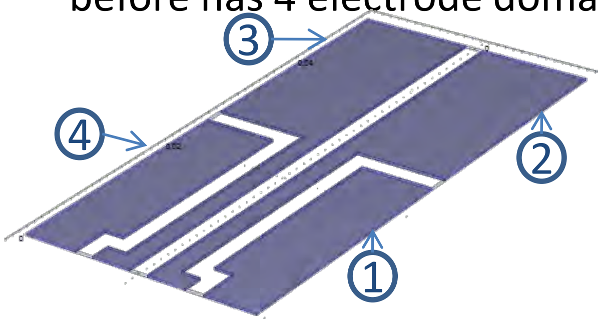
- **Modeling challenge**
  - Same as in case of 2D
    - Fine mesh, high aspect ratio
  - Even simple scaling challenging

~300,000 nDOF

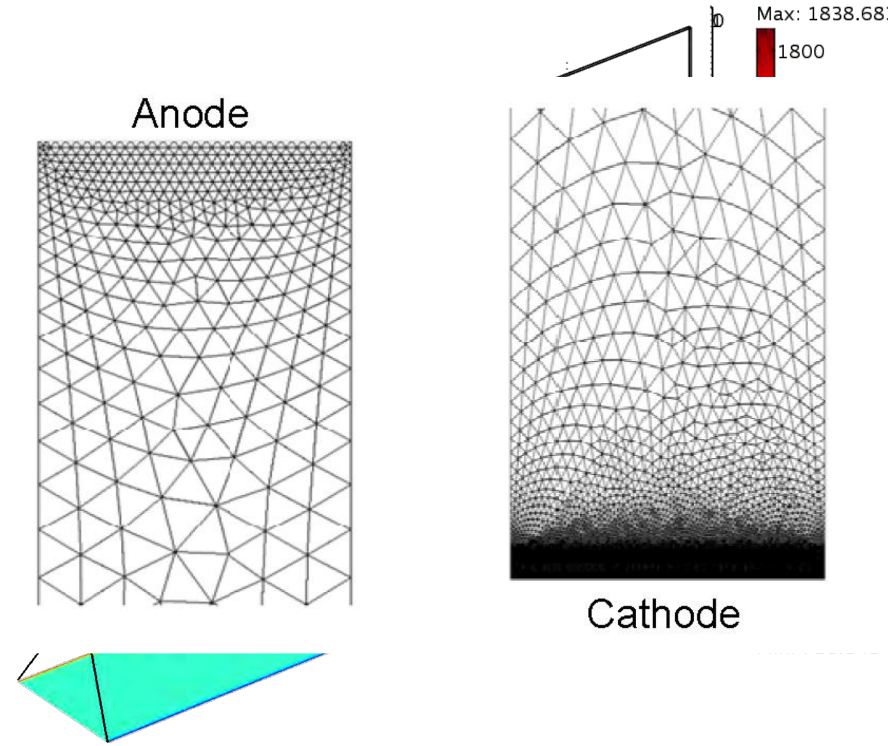


IPMC – 3D modeling approach

- **There are 1…n different electrodes in case of a patterned IPMC.**
  - For instance, the specimen shown before has 4 electrode domains:



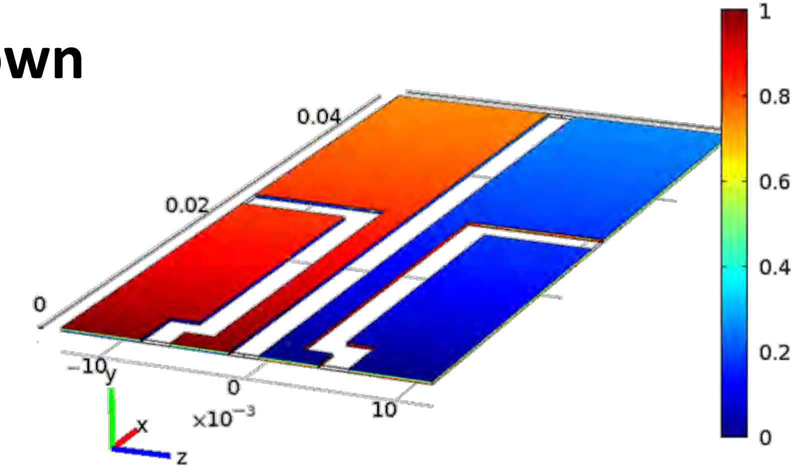
- **Calculate the concentration C for each electrode**
  - 2D domain: 200µm x 100 µm
  - Dense mesh near the boundaries
  - Very fast calculation
- **Save the calculation results for each time step**
- **Extrude (and scale) the saved values**

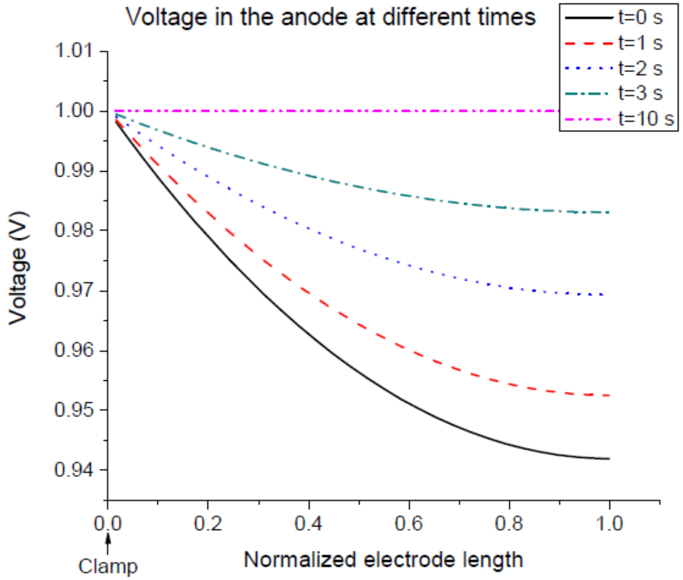


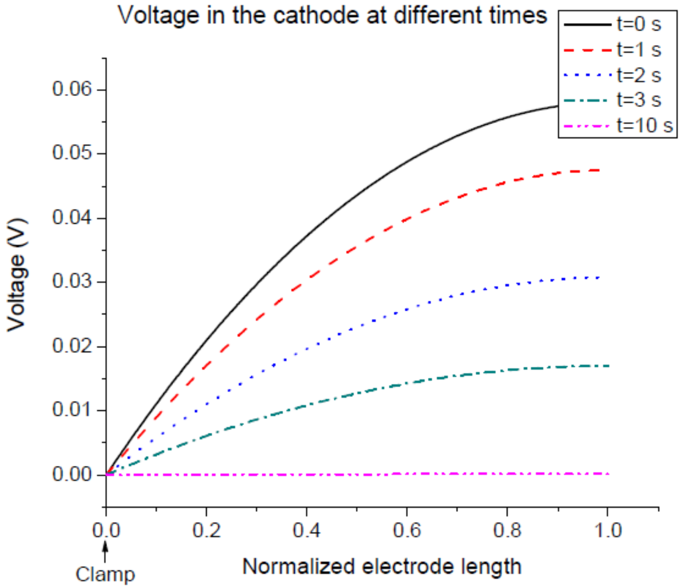
- **Calculate the 3D bending**

IPMC – 3D modeling approach

- **Extruded and scaled voltage shown**
  - Positive voltage applied to the electrodes on left
  - The electrodes on right are grounded
  - Notice the voltage drop





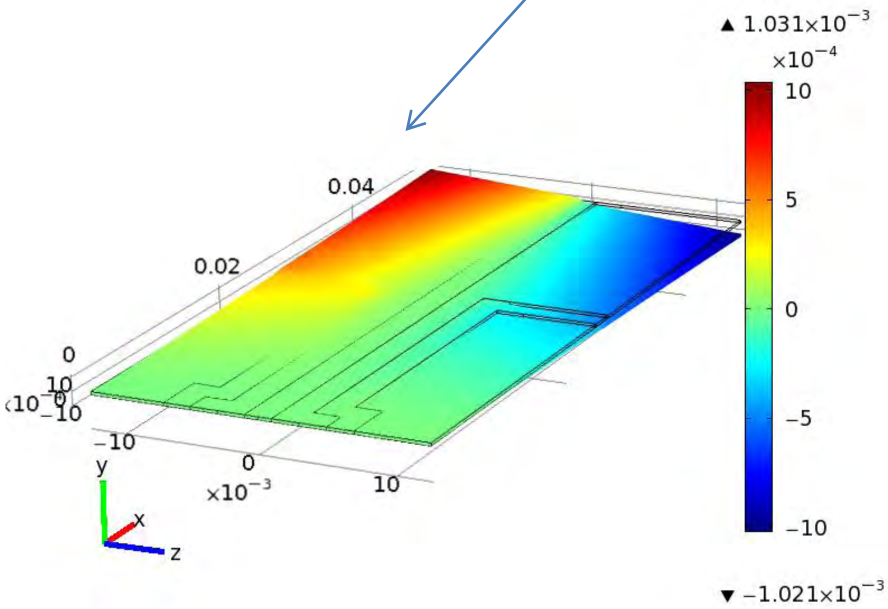


IPMC – 3D modeling result

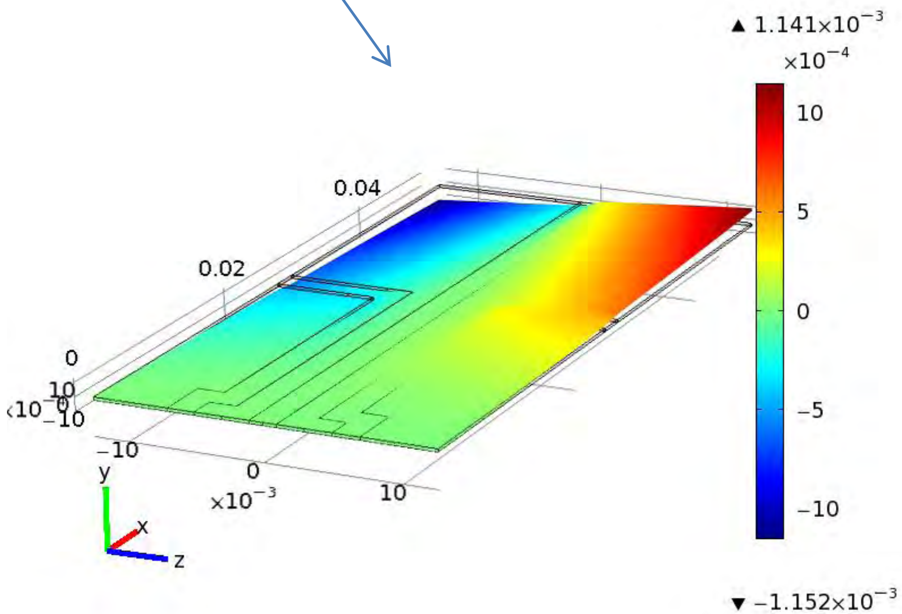
- **3D actuation calculation**
  - Color: *y*-directional displacement

$$V_1 = 5\,[V]\sin(2\pi t)\,,$$
$$V_2 = -5\,[V]\sin(2\pi t)$$

t = 0.25 s

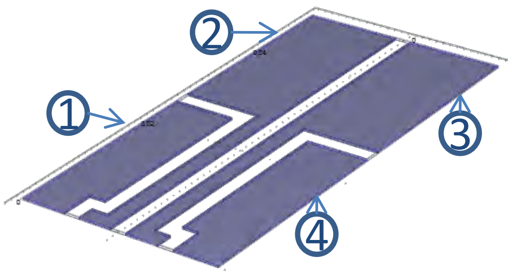


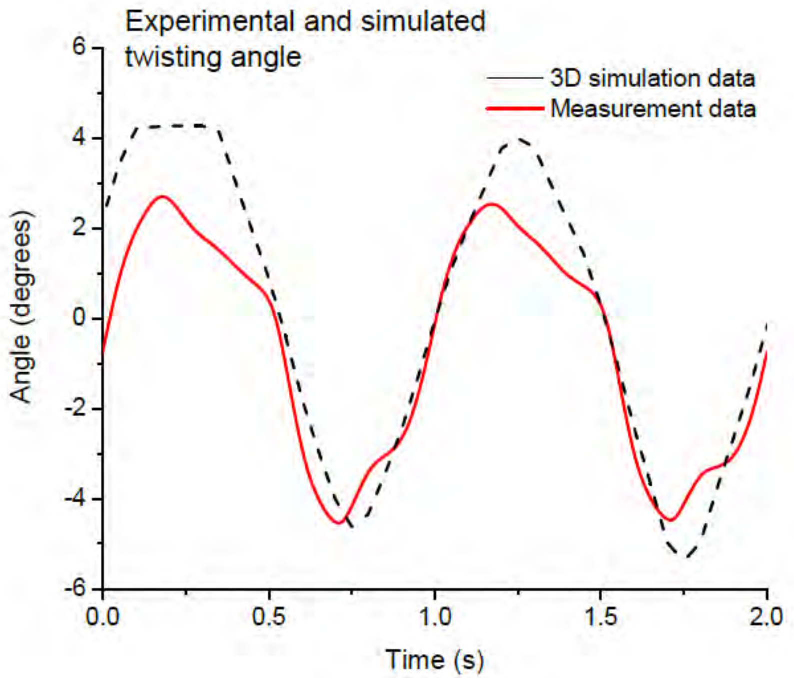
t = 0.75 s

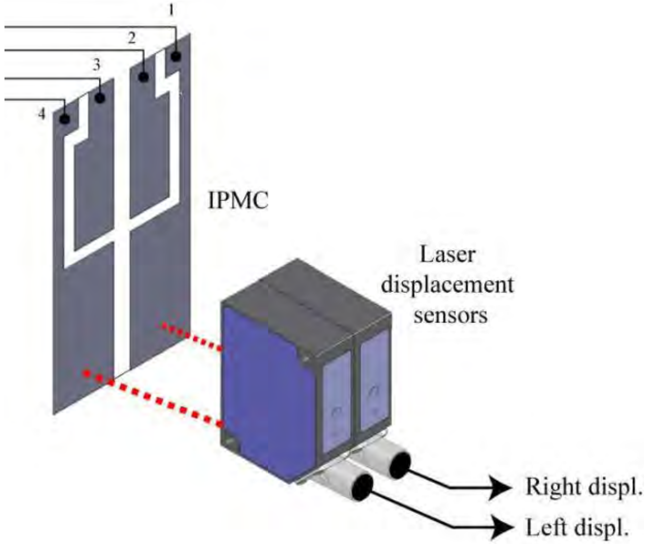


IPMC – 3D modeling and experiment

- **Measured versus calculated twisting angle**
  - Applied voltages
    - Electrodes 1, 2: $V_1 = 5\,[V]\sin(2\pi t)\,,$
    - Electrodes 3, 4: $V_2 = -5\,[V]\sin(2\pi t)$

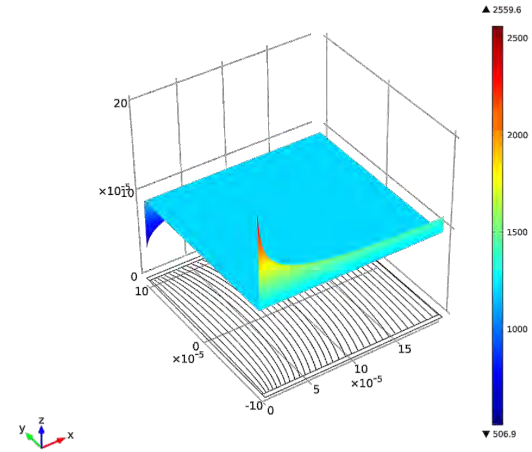


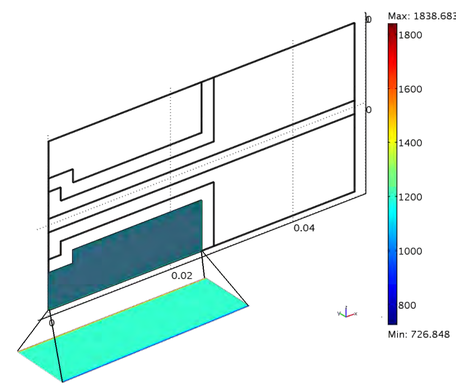




Conclusions

- **Conclusions**
  - A physics based model of IPMC was implemented in Comol Multiphysics
    - Electrode currents were coupled to the ionic currents using *Projection coupling* feature
    - Calculated charge density was projected to the full scale 2D domain to calculate deformation
  - A full scale 3D actuation model was developed for patterned IPMCs
    - 2D projection and extrusion was used
    - The calculations results were also validated
  - Overall, using the coupling features of Comsol, a rather complicated multi-physics problem was solved on a high aspect ratio geometry





Thank you

- **Acknowledgements**

  - We acknowledge the financial support from the Office of Naval Research and Estonian Archimedes Foundations

- **Questions?**