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Thickness Optimization of a Piezoelectric Converter for Energy Harvesting

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Introduction

Extensive diffusion of sensing nodes and sensing networks
(automotive, factory automation, entertainment, environment monitoring, security systems,…)

Main issue: **power supply**

Batteries

- ⇩ limited lifetime
- ⇩ recharging/replacement/disposal
- ⇩ cost

Power harvesting

- ⇧ in principle unlimited lifetime
- ⇧ unattended operation
- ⇩ sometimes limited output power

Environment

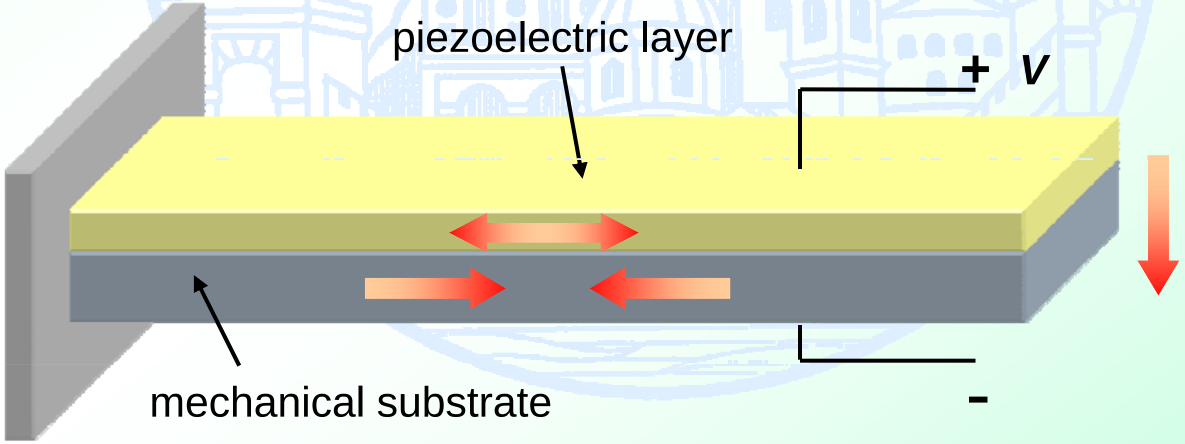
✓ Solar energy
✓ Mechanical vibrations
✓ Temperature gradients
✓ …

Mechanoelectrical energy conversion

- Conversion techniques
  - electromagnetic (inductive)
  - electrostatic (capacitive)
  - **piezoelectric**

Direct piezoelectric effect: surface charge induced by a mechanical stress

- Piezoelectric energy converter
  - unimorph cantilever shape (thick-film, MEMS technologies)

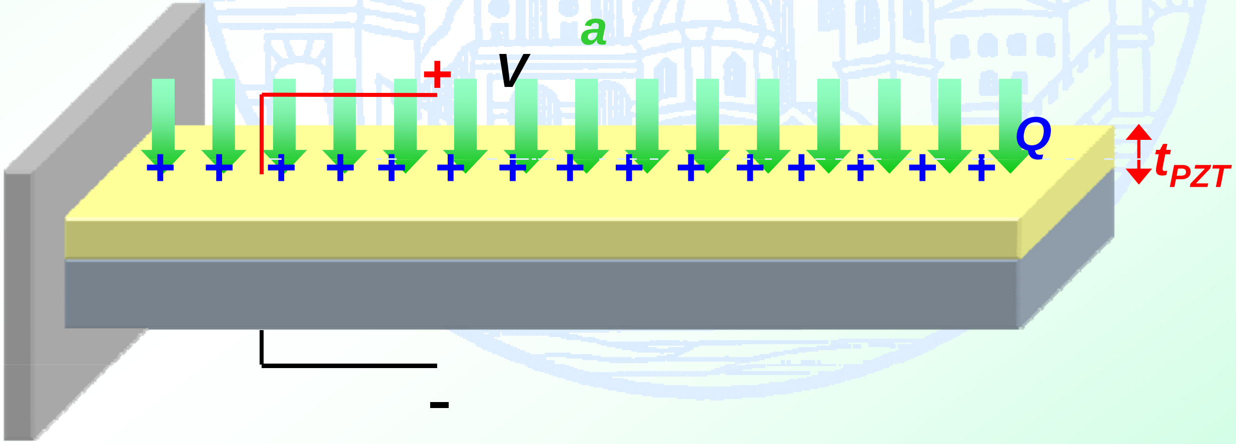


Use of COMSOL

- Improvement of the converted energy

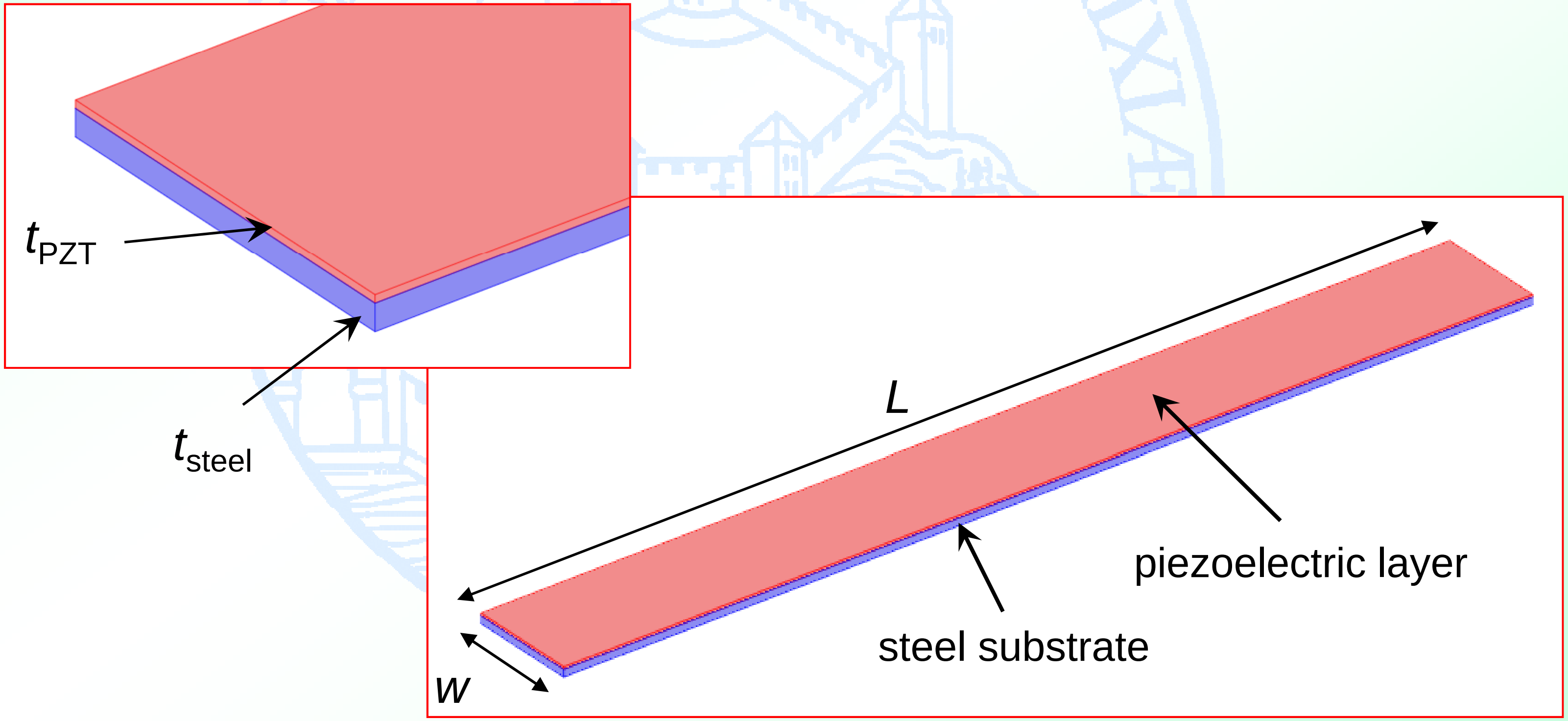
  Optimization of the dimensions
  - piezoelectric layer thickness

- Application modes
  - piezoelectric: mechanical / electrical behaviour
    - sinusoidal vertical acceleration application
    - generated charge / voltage
  - moving mesh: thickness change



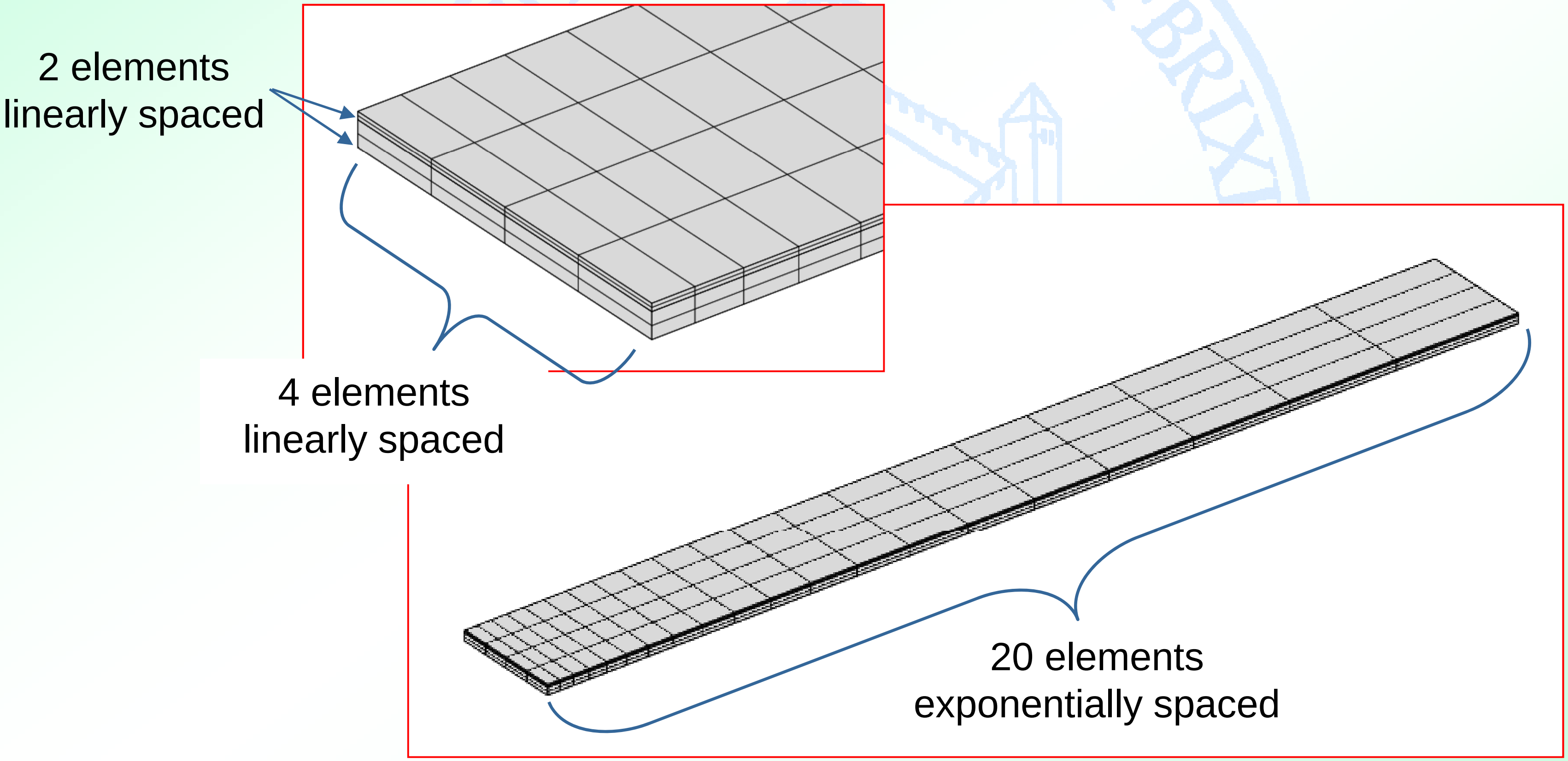
Geometry

- 3D cantilever
  - lenght L = 27 mm;
  - width w = 3 mm;
  - steel thickness t_{steel}= 200 μm;
  - piezoelectric layer thickness t_{PZT} = 60 μm (poled along thickness)



Mesh

- Mapped mesh
  - 320 quad elements; 11808 degrees of freedom



2 elements
linearly spaced

4 elements
linearly spaced

20 elements
exponentially spaced

Governing equations

- Piezoelectric layer
  - strain-charge form

$$S = s^E T + dE$$

$$D = \varepsilon^T E + dT$$

- S = mechanical strain
- T = mechanical stress [N/m^2]
- s^E = elastic compliance [Pa^{-1}]
- d = piezoelectric coefficient [C/N]
- D = electric displacement [C/m^2]
- E = electric field [V/m]
- ε^T = dielectric permittivity [F/m]

$$s^E = \begin{bmatrix} 50 & -20 & -20 & 0 & 0 & 0 \\ -20 & 50 & -20 & 0 & 0 & 0 \\ -20 & -20 & 50 & 0 & 0 & 0 \\ 0 & 0 & 0 & 70 & 0 & 0 \\ 0 & 0 & 0 & 0 & 70 & 0 \\ 0 & 0 & 0 & 0 & 0 & 70 \end{bmatrix} \times 10^{-12} \, Pa^{-1}$$

$$d = \begin{bmatrix} 0 & 0 & 0 & 0 & 11 & 0 \\ 0 & 0 & 0 & 11 & 0 & 0 \\ -2.5 & -2.5 & 5 & 0 & 0 & 0 \end{bmatrix} \times 10^{-12} \, CN^{-1}$$

$$\varepsilon^T = \begin{bmatrix} 50 & 0 & 0 \\ 0 & 50 & 0 \\ 0 & 0 & 50 \end{bmatrix} \times \varepsilon_0$$

$$\rho = 3000 \ kg \cdot m^{-3}$$

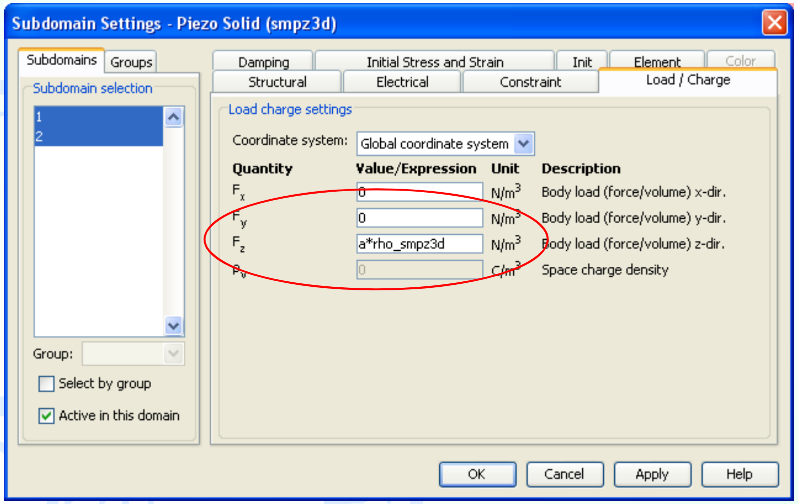
- Steel layer

$$S = sT$$

$$s = 5x10^{-12} \, Pa^{-1}$$

Subdomain and boundary conditions

- Vertical acceleration
  - Body load $F_z = a\rho$
    - $a = 0.1\ g$
    - ρ = *material density*



Subdomain selection: 1, 2

Group:

☐ Select by group

☑ Active in this domain

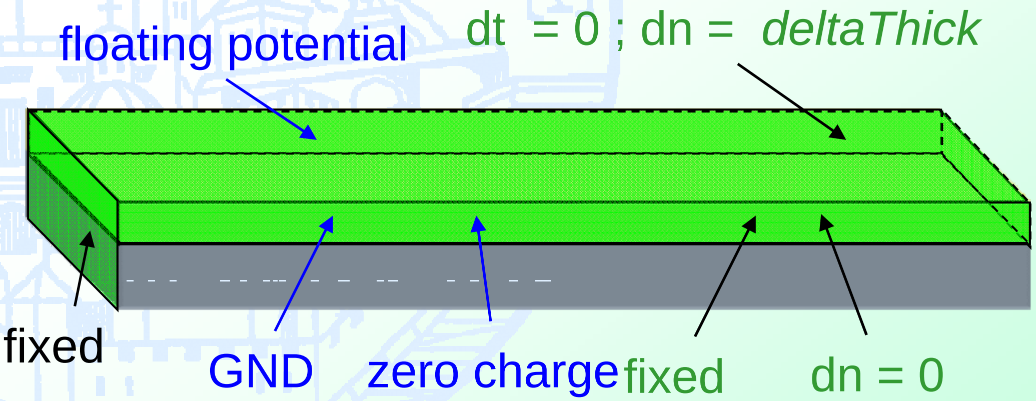
Load charge settings

Coordinate system: Global coordinate system

Quantity	Value/Expression	Unit	Description
F_x	0	N/m^3	Body load (force/volume) x-dir.
F_y	0	N/m^3	Body load (force/volume) y-dir.
F_z	a*rho_smpz3d	N/m^3	Body load (force/volume) z-dir.
ρ_v	0	C/m^3	Space charge density

- Mechanical boundary conditions
  - clamped end

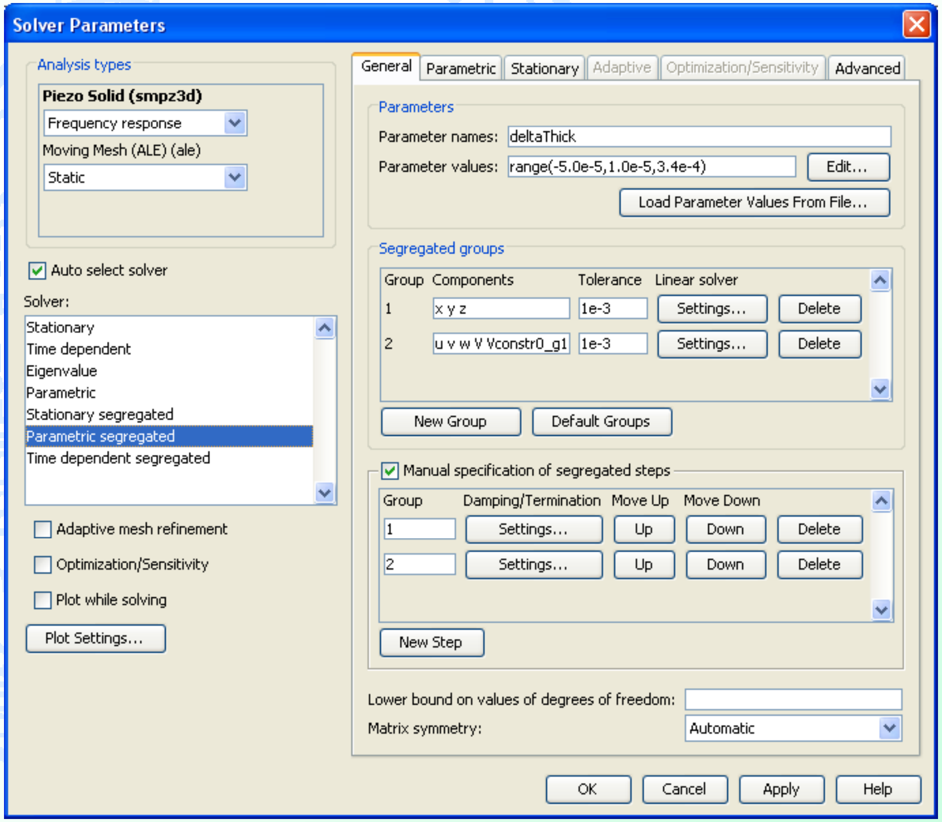
- Electrostatic boundary conditions
  - bottom surface: *grounded*
  - upper surface: *floating potential*
  - other surfaces: *zero charge*



- Mesh boundary conditions
  - bottom surface: clamped
  - vertical surfaces: normally clamped
  - upper surface: tangentially clamped, normally displaced (*deltaThick*)

Solver parameters

- Parametric segregated solver
  - group 1: moving mesh, static analysis
    - *deltaThick:* -50 µm → 340 µm
  - group 2: piezoelectric variables, frequency response
    - frequency = 10 Hz



Solver Parameters

Analysis types

Piezo Solid (smpz3d): Frequency response

Moving Mesh (ALE) (ale): Static

☑ Auto select solver

Solver:
- Stationary
- Time dependent
- Eigenvalue
- Parametric
- Stationary segregated
- Parametric segregated (selected)
- Time dependent segregated

☐ Adaptive mesh refinement

☐ Optimization/Sensitivity

☐ Plot while solving

Parameters

Parameter names: deltaThick

Parameter values: range(-5.0e-5,1.0e-5,3.4e-4)

Segregated groups

Group	Components	Tolerance	Linear solver	
1	x y z	1e-3	Settings...	Delete
2	u v w V Vconstr0_g1	1e-3	Settings...	Delete

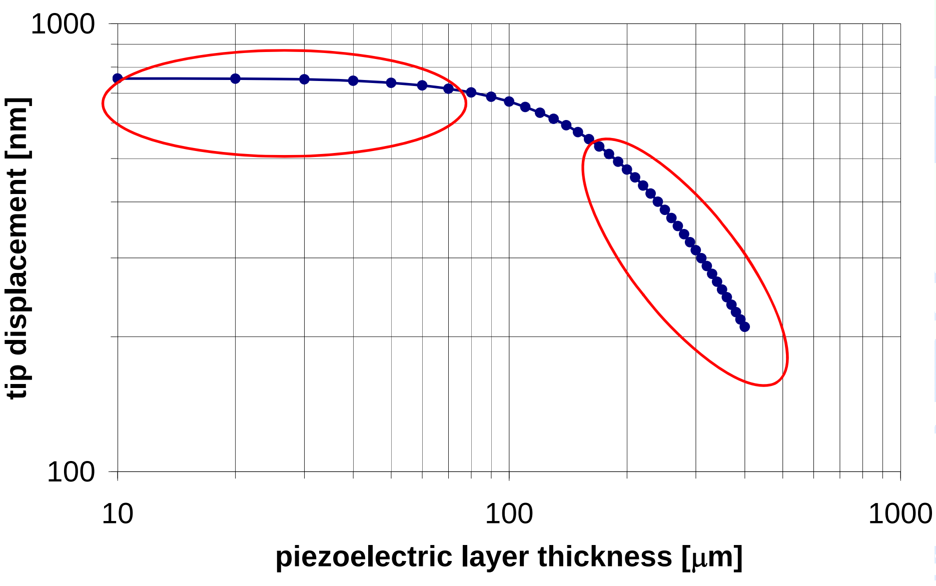
☑ Manual specification of segregated steps

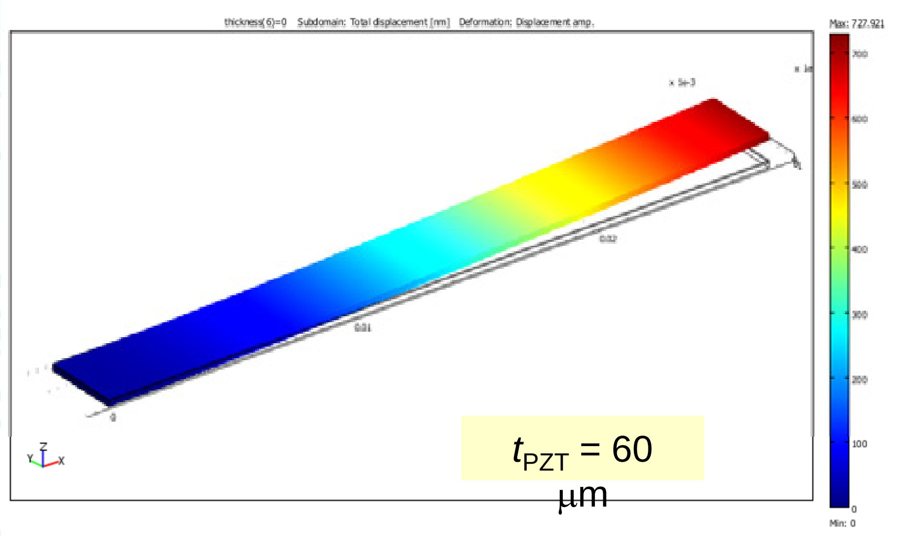
Group	Damping/Termination	Move Up	Move Down	
1	Settings...	Up	Down	Delete
2	Settings...	Up	Down	Delete

Lower bound on values of degrees of freedom:

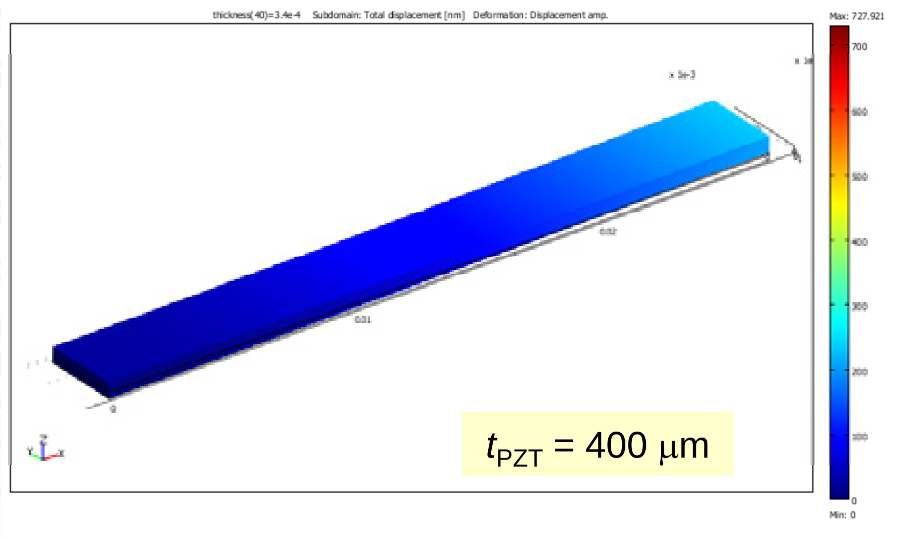
Matrix symmetry: Automatic

Results – tip displacement





t_{PZT} = 60 µm



t_{PZT} = 400 µm

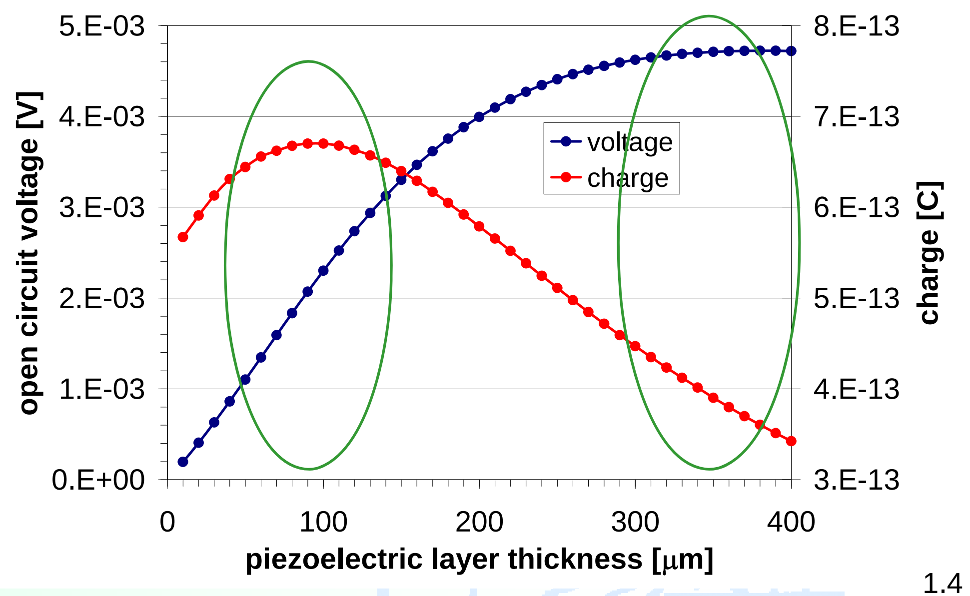
PZT rigidity << steel rigidity

tip displacement ≈ const

PZT rigidity >> steel rigidity

tip displacement ≈ $1/t_{PZT}^{n}$

Results – electrical output

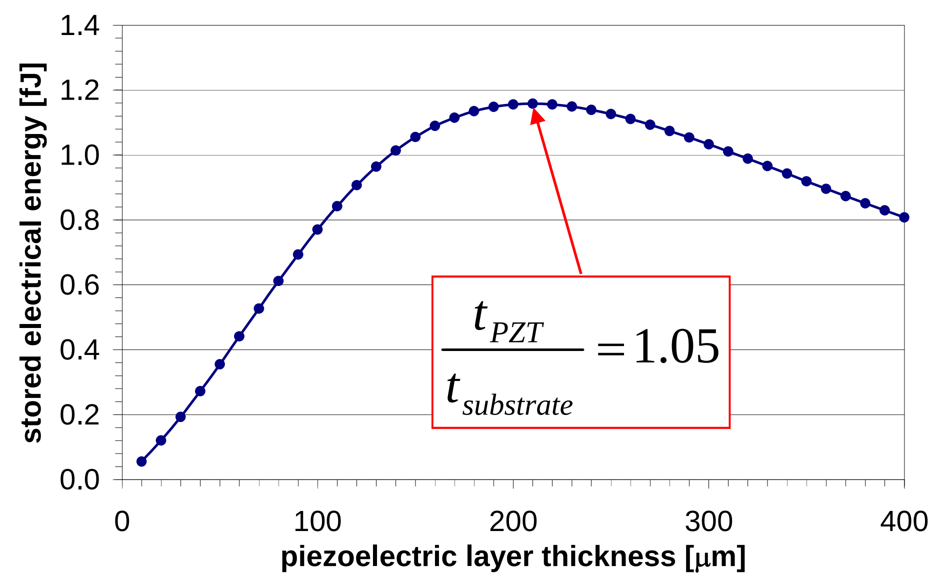


PZT rigidity << steel rigidity
charge: maximum
voltage: increases

PZT rigidity >> steel rigidity
charge: decreases
voltage ≈ const

- Stored electrical energy

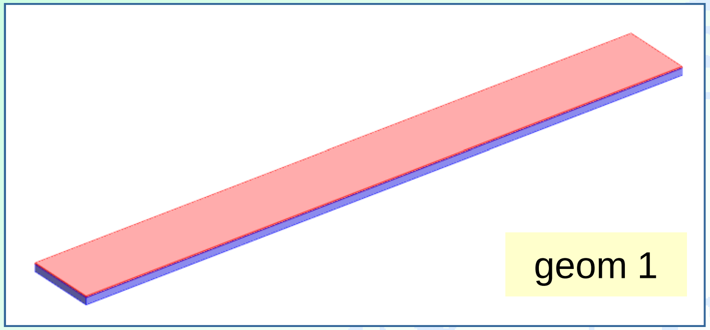
$$E = \frac{1}{2} QV$$

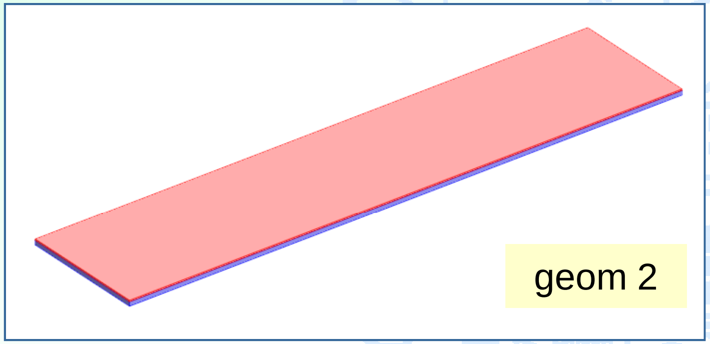


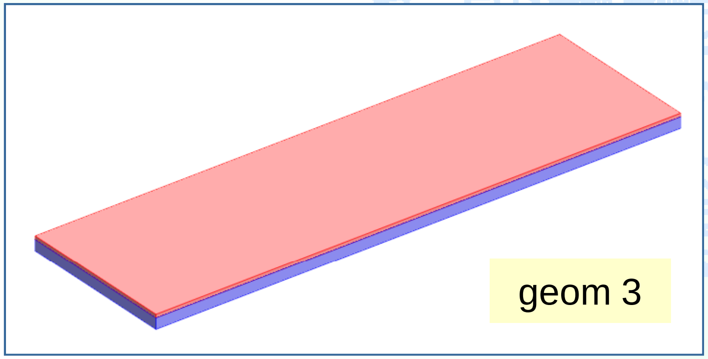
$$\frac{t_{PZT}}{t_{substrate}} = 1.05$$

Results – influence of the geometry

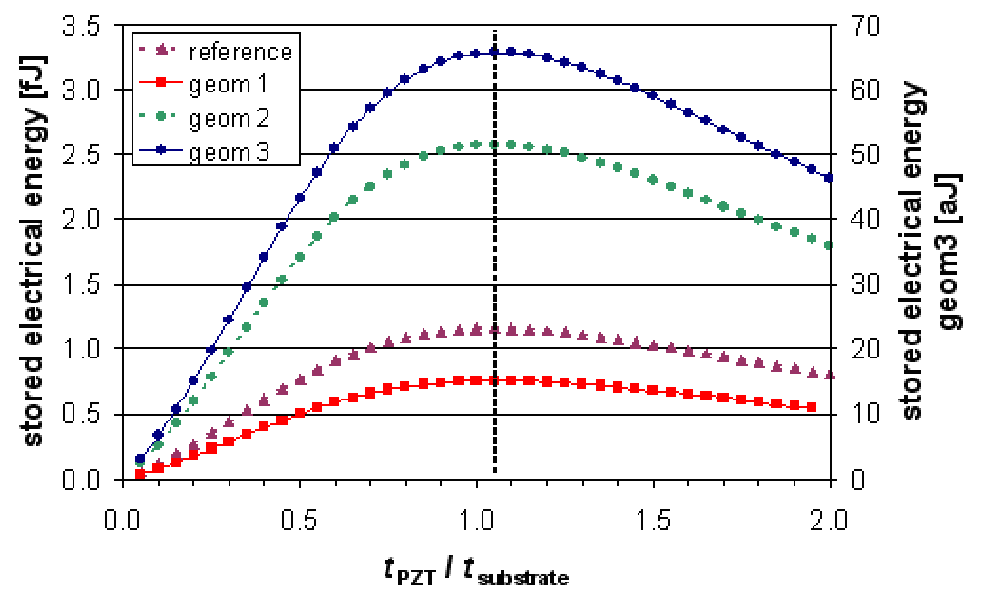
- Different geometries







	Substrate thickness [µm]	Width [mm]	Length [mm]
reference	200	3	27
geometry 1	300	3	27
geometry 2	200	6	27
geometry 3	200	3	10



Conclusions

- FEM simulations used for optimizing the geometrical dimensions of a piezoelectric energy converter
- Geometry with parametrized thickness
  - piezoelectric application mode
  - moving mesh application mode

- The optimal $t_{\mathrm{PZT}}/t_{\mathrm{substrate}}$ was found for maximizing the electrical energy
- The optimal $t_{\mathrm{PZT}}/t_{\mathrm{substrate}}$ value is independent from the converter dimensions

- This model is a specific example of using moving mesh for device geometry optimization