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ANSYS

EPCOS

EFFICIENT MULTI-PHYSICS MODELING OF THE DYNAMIC RESPONSE OF RF-MEMS SWITCHES

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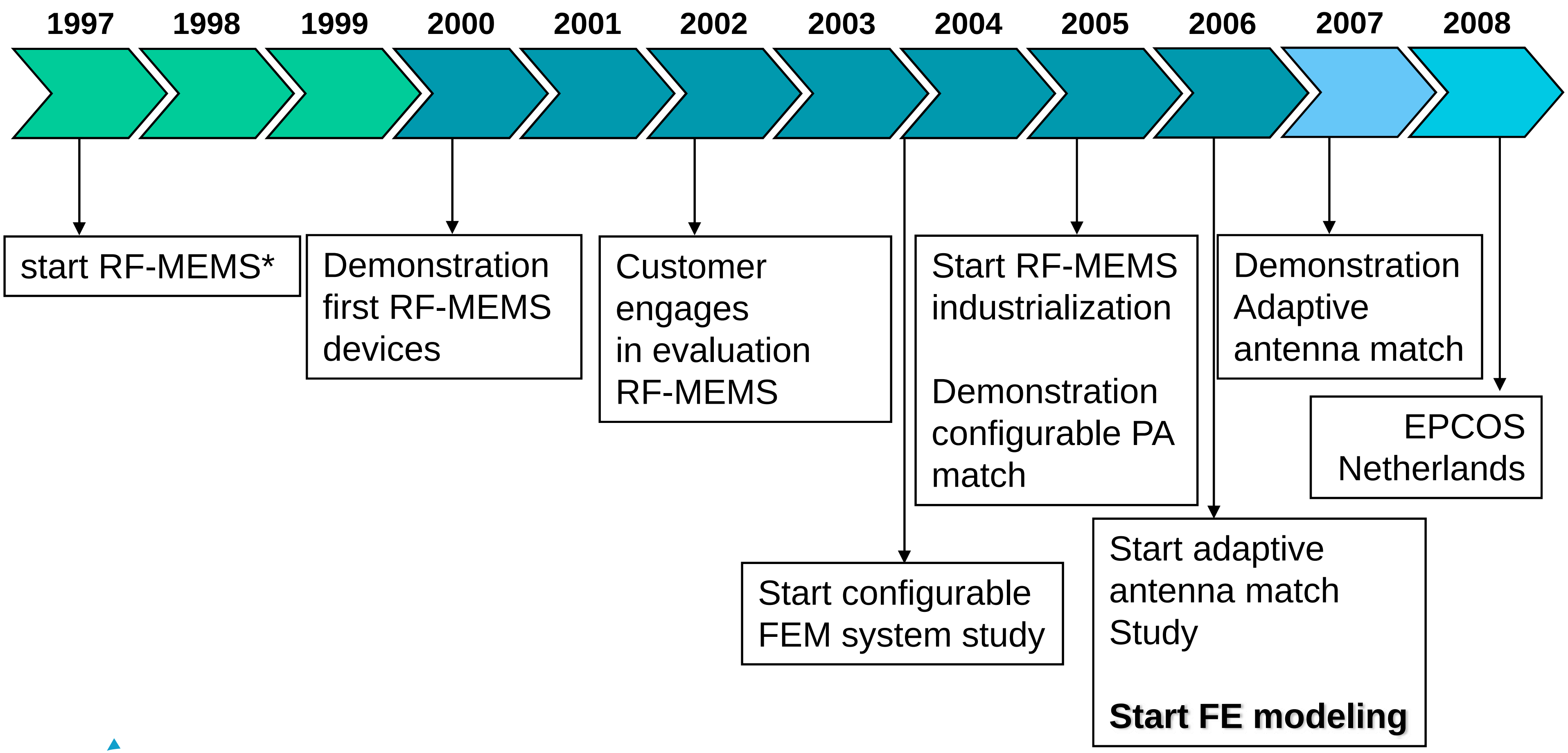
Outline

- Intro RF-MEMS at EPCOS Netherlands
- Physics of capacitive MEMS switch
- FE model:
    - Coupling of physics domains
    - Obtaining the static solution
    - Homogenization of surface roughness
    - Non-linear Reynolds for fluid / large signal transient
- Transient results & calibration with measurement
- Conclusion & outlook

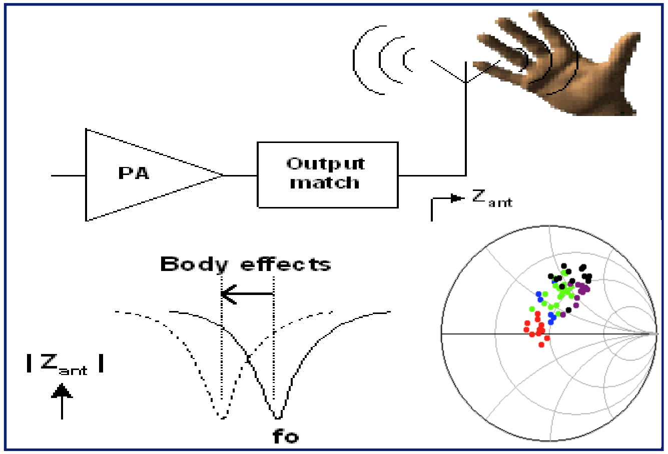
History of RF-MEMS and tuneable RF systems



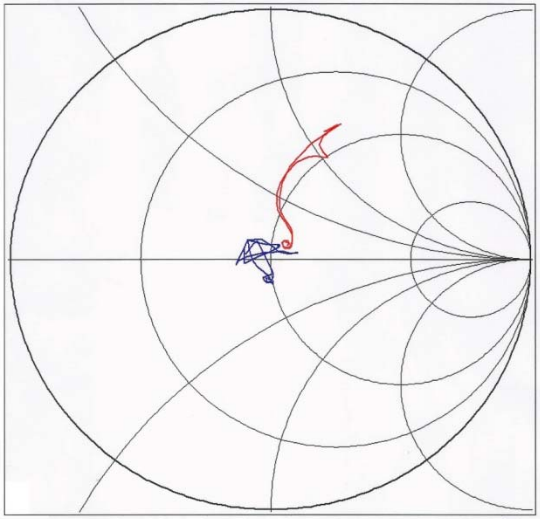
* Program started at Philips Research

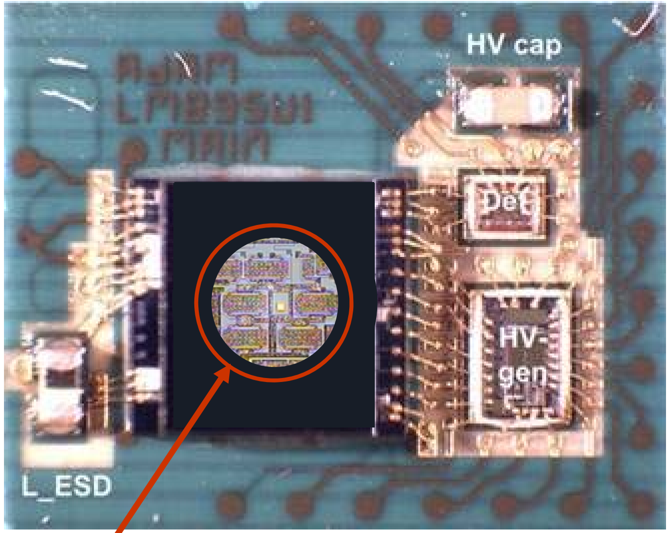
Adaptive multi-band antenna optimized performance

- A plug and play antenna module
  - frequency band configurable
  - automatic performance optimization
- increased average RF output power
- increased battery time
- lower VSWR, more system margin



Measurement data LB:
• uncorrected hand effects
• hand effects corrected by AdAM

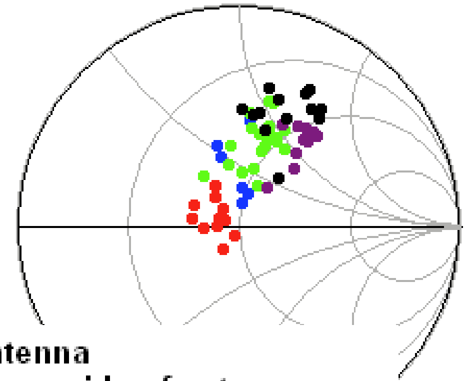




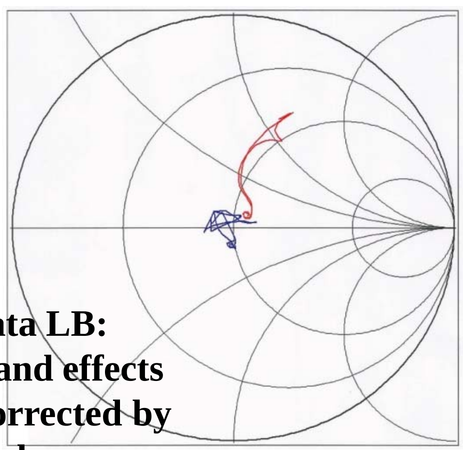
Multiphysics modeling required

Introduction RF-MEMS: Application example

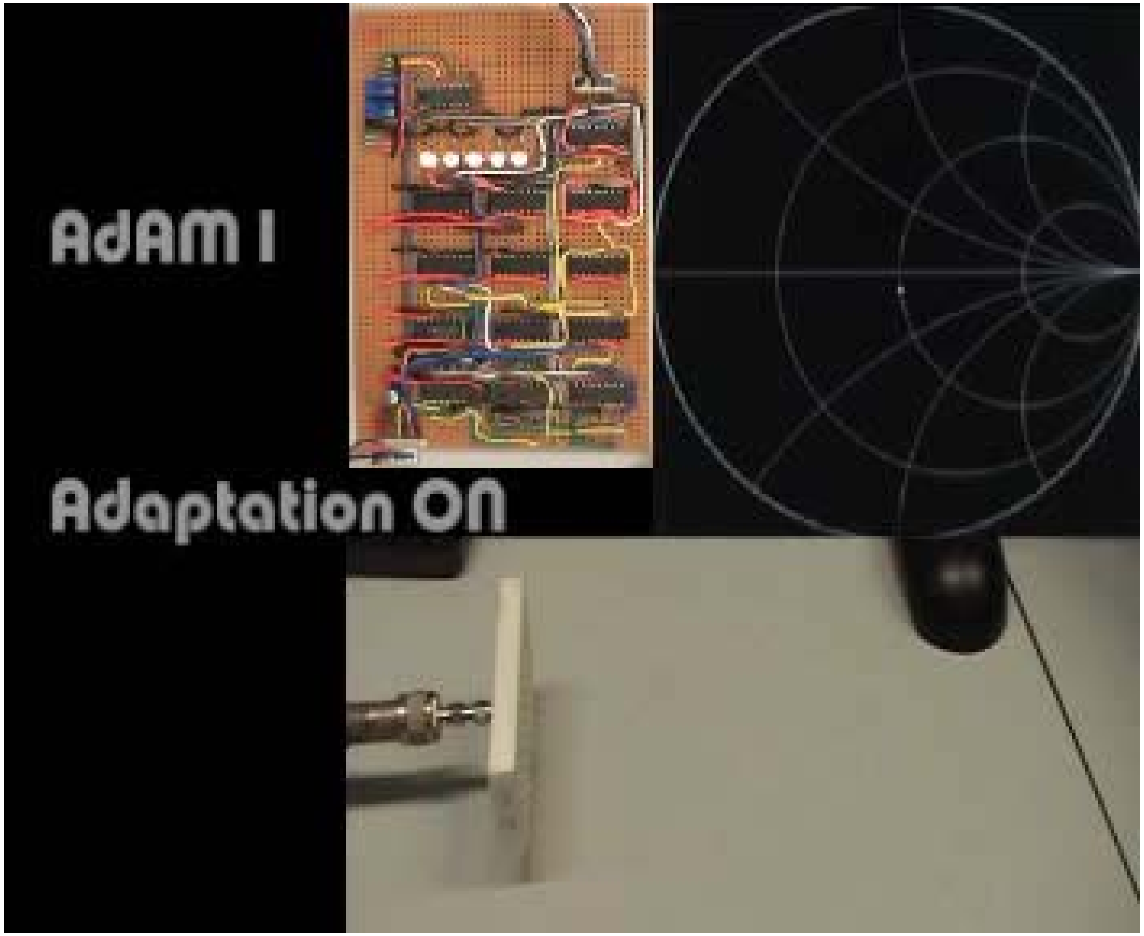
Hand detuning effects effectively corrected – AdAM



- hand not on antenna
- thumb or finger on side of antenna
- thumb and fingers on side of antenna
- hand and/or fingers on antenna
- hand and/or fingers over top of antenna

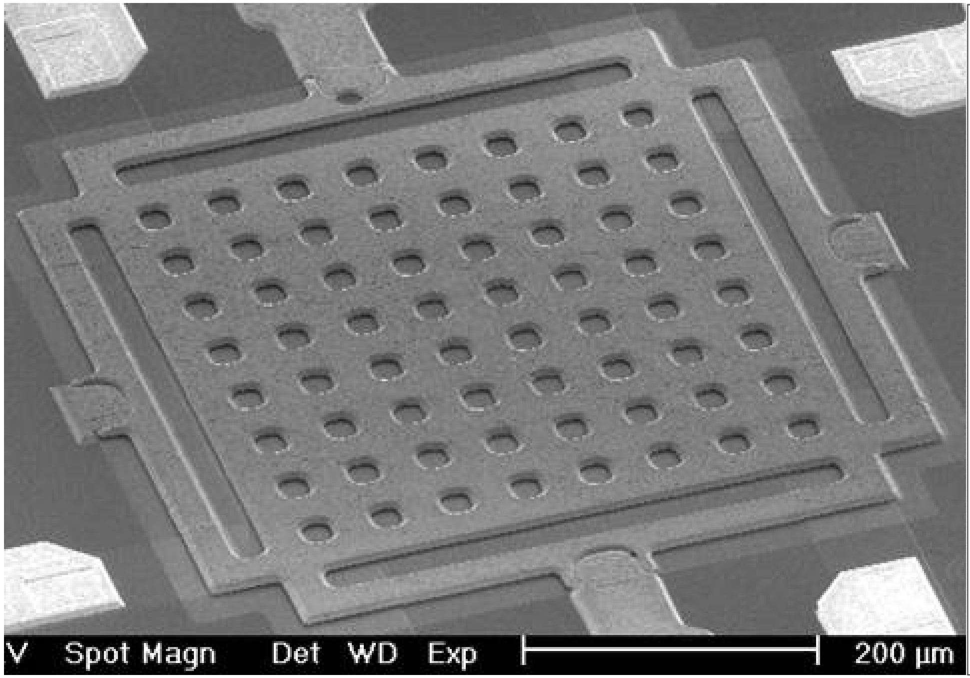


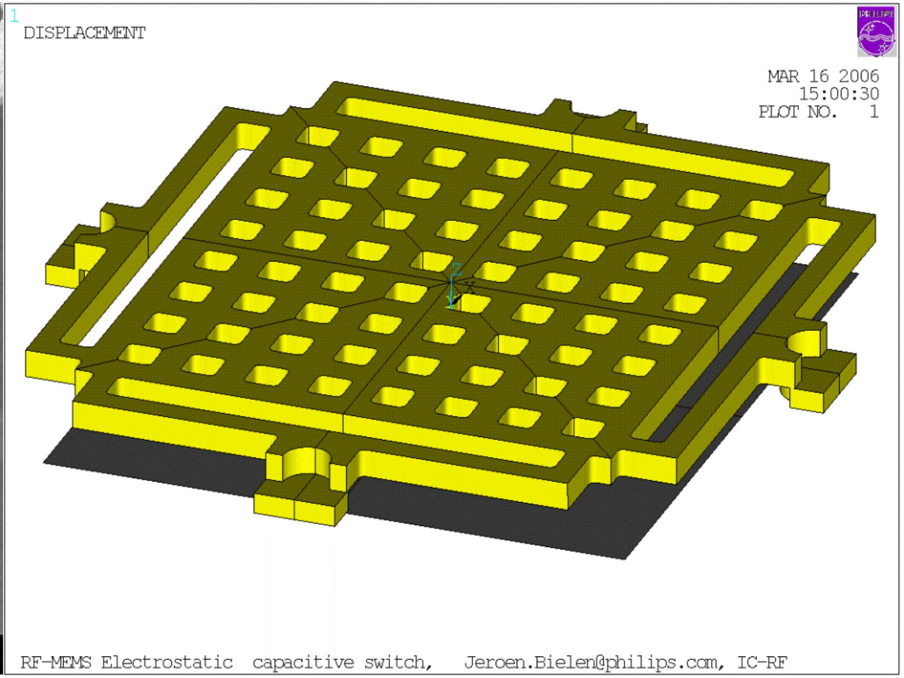
Measurement data LB:
- uncorrected hand effects
- hand effects corrected by AdAM-1 module



RF-MEMS capacitive switch

- Plate suspended by beams above bottom electrode covered with dielectric
- When a DC voltage is is supplied the plate is pulled-down thus creating a 20x larger capacitance between the electrodes

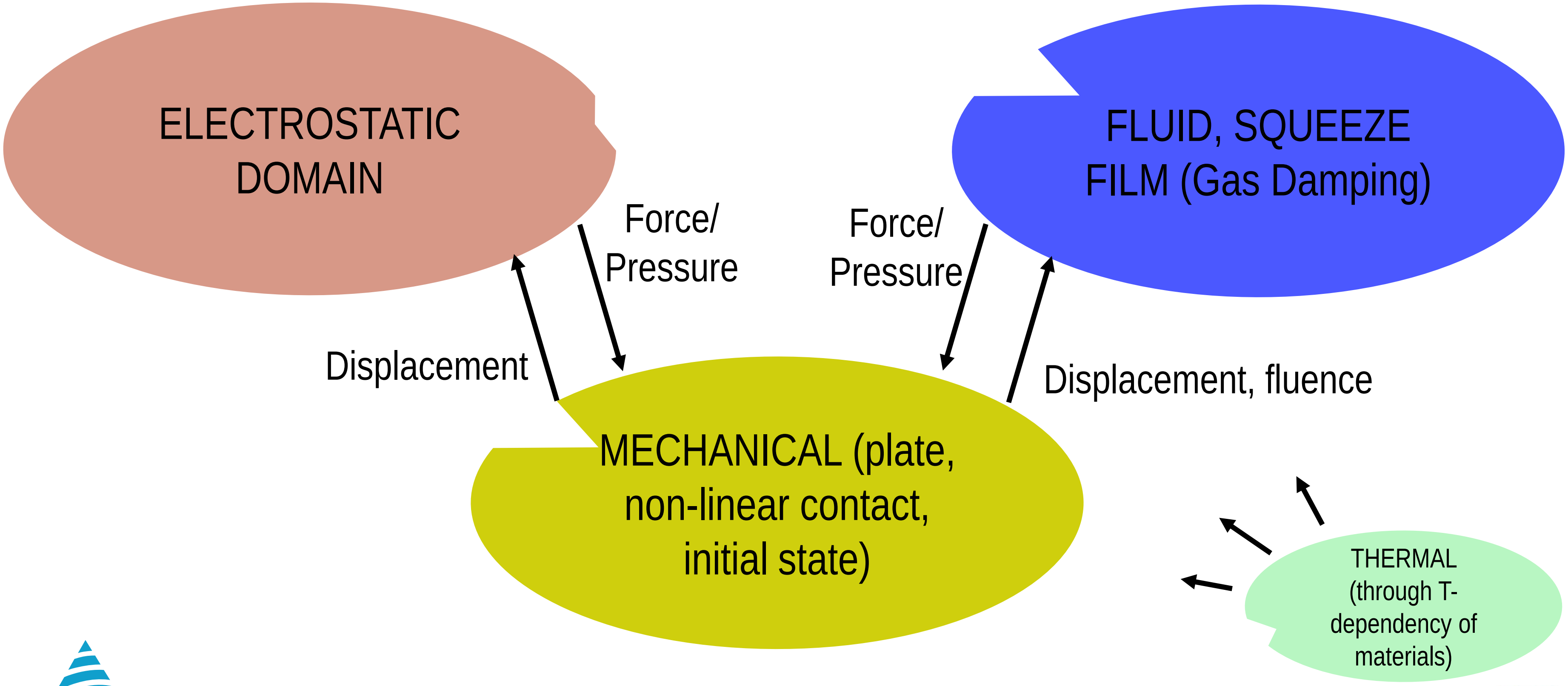




Finite element model: key to predictive design

Capacitive switch is multi-physics problem:

- Bi-directional coupling between three different physics domains
- Non-linearities cause pull-in instability and convergence problems

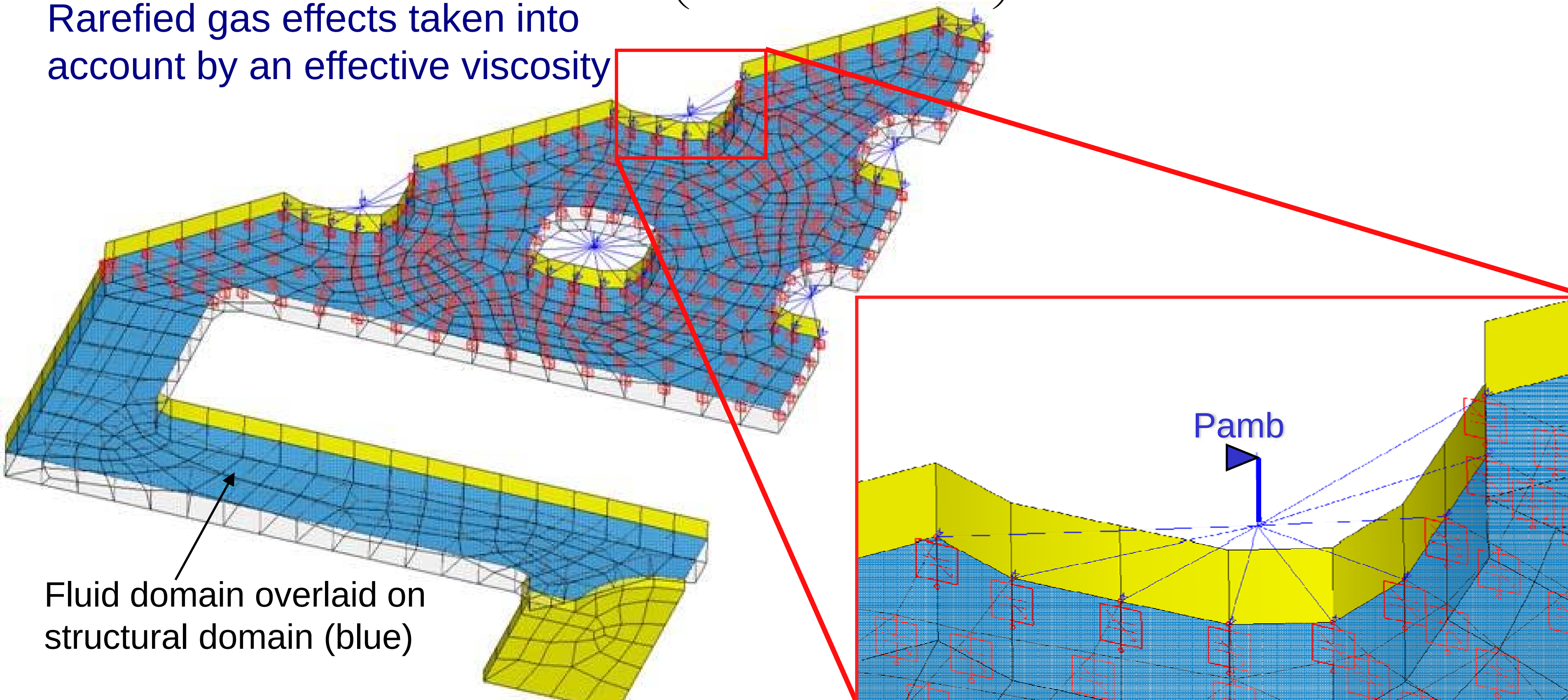


Directly coupled fluid-electro-mechanical model

Fluid-mechanical coupling with iso-thermal non-linear compressible Reynolds equation in directly coupled element:

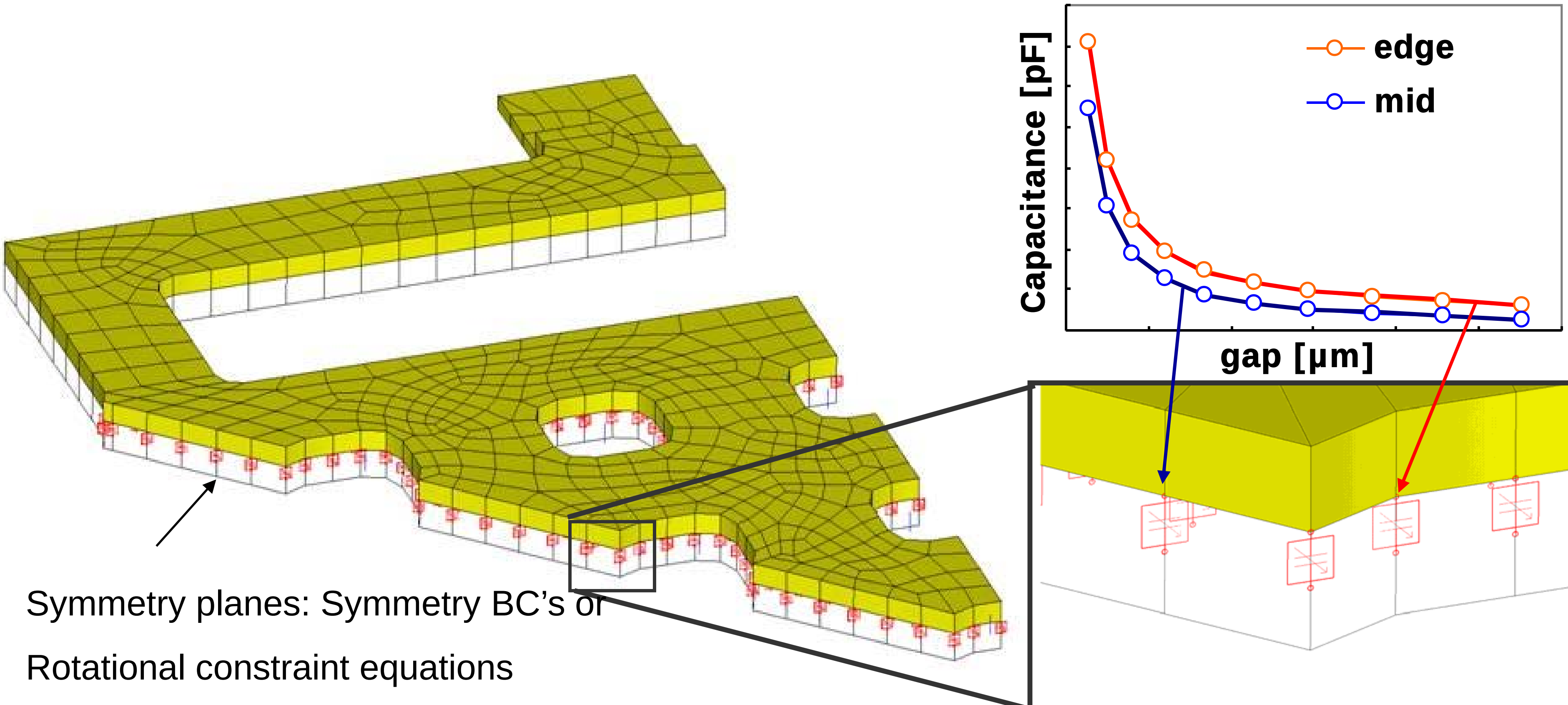
$$\frac{H}{p}\frac{\partial p}{\partial t}+\frac{\partial H}{\partial t}=\frac{H^{3}}{p12\mu}\left(\left(\frac{\partial p}{\partial x}\right)^{2}+\left(\frac{\partial p}{\partial y}\right)^{2}\right)+\frac{H^{3}}{12\mu}\nabla^{2}p$$

Rarefied gas effects taken into account by an effective viscosity



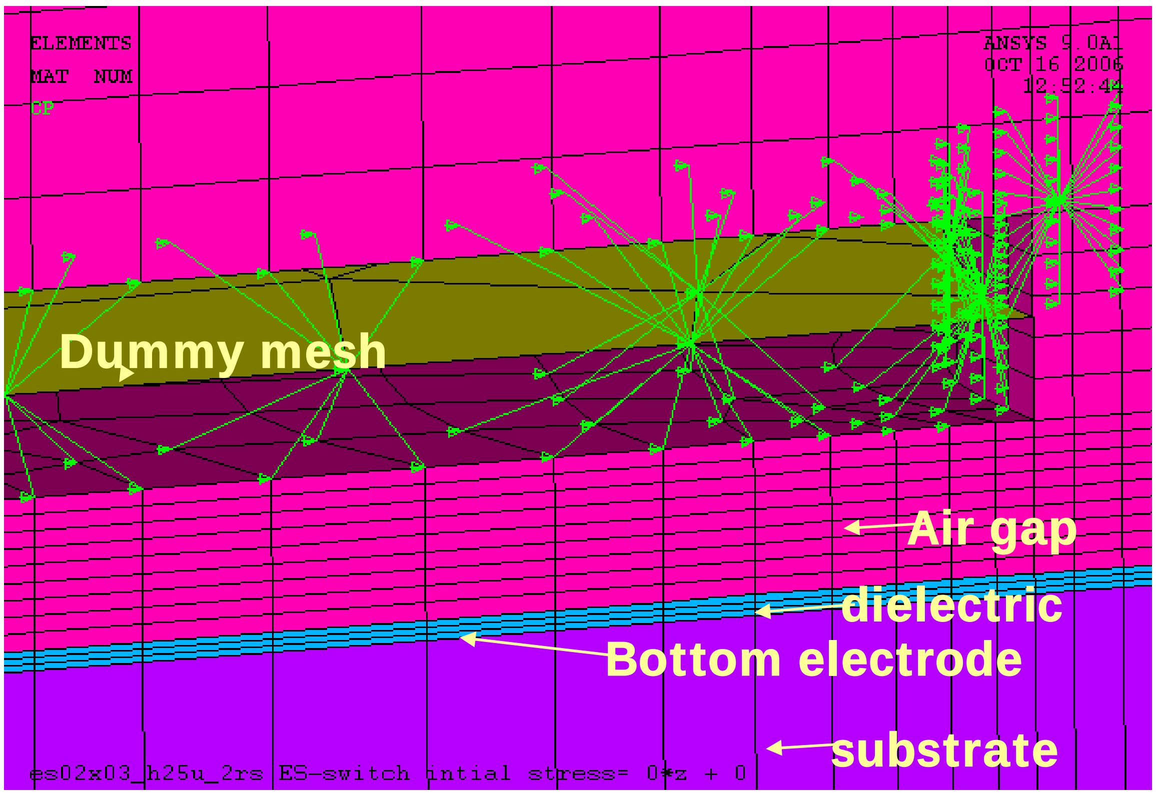
Directly coupled electro-mechanical model

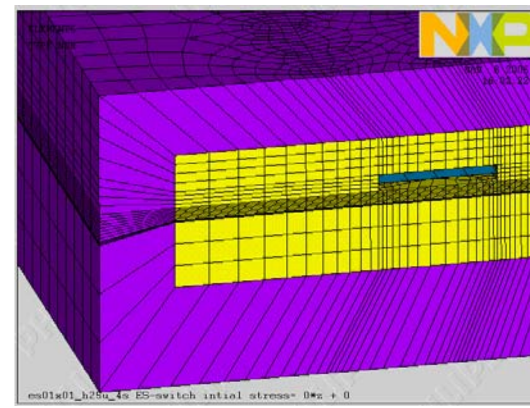
- Electro-mechanical coupling very efficient with transducer elements (only one mechanical DOF & 1 Volt DOF per node)
- C(z) of transducers from prior electrostatic simulation

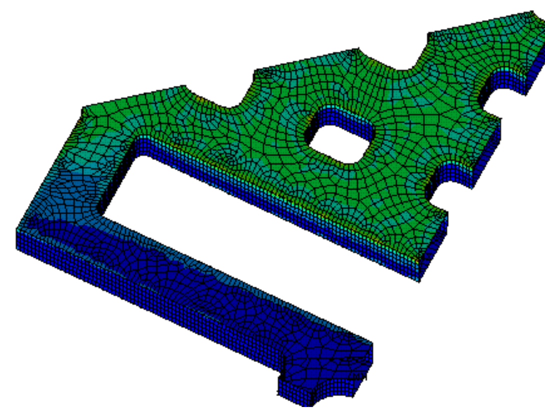


Electrostatic model

- Dummy mesh used to map charge from electrostatic mesh to nearest mechanical node allows for dissimilar meshes
- Electrostatic simulation repeated for various (uniform) gap heights



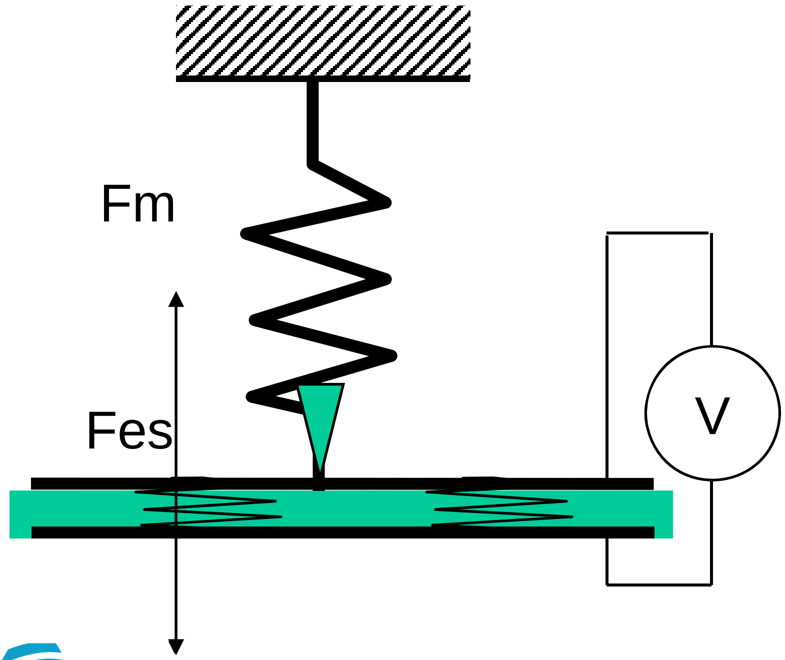


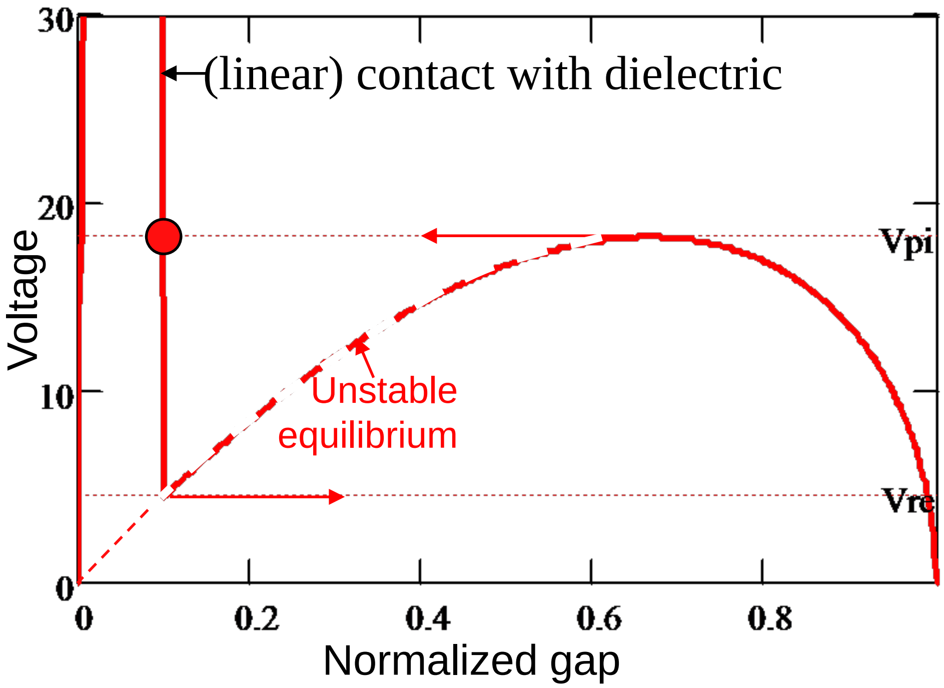


Solving Pull-in instability: DIPIE+

- Displacement iterations scheme (DIPIE) can solve pull-in instability because for every displacement there is only one voltage solution

$$Fm + Fes = k \cdot (z - gap0) + \frac{\varepsilon 0 \cdot Area \cdot V^2}{2 \cdot z^2} = 0$$



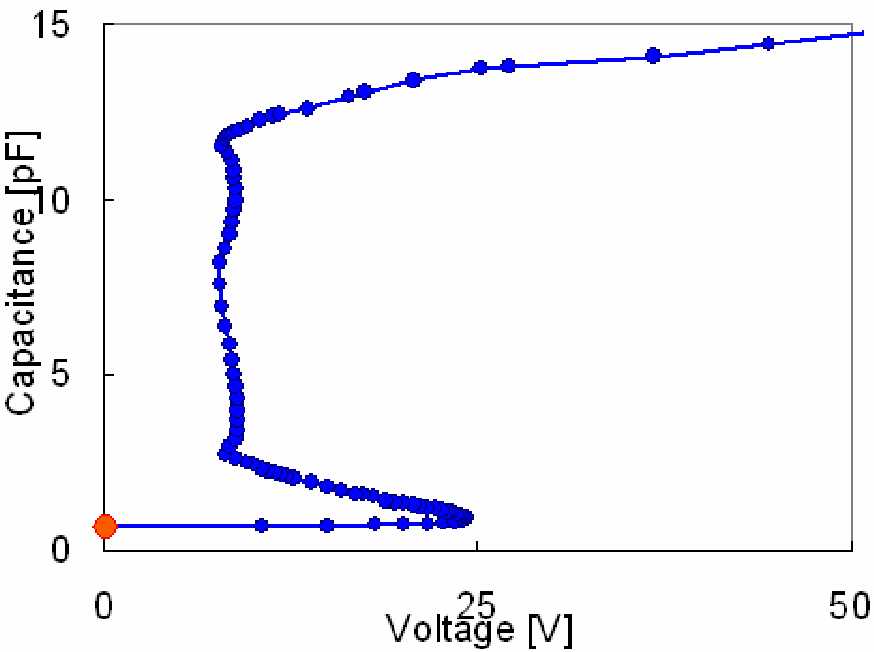


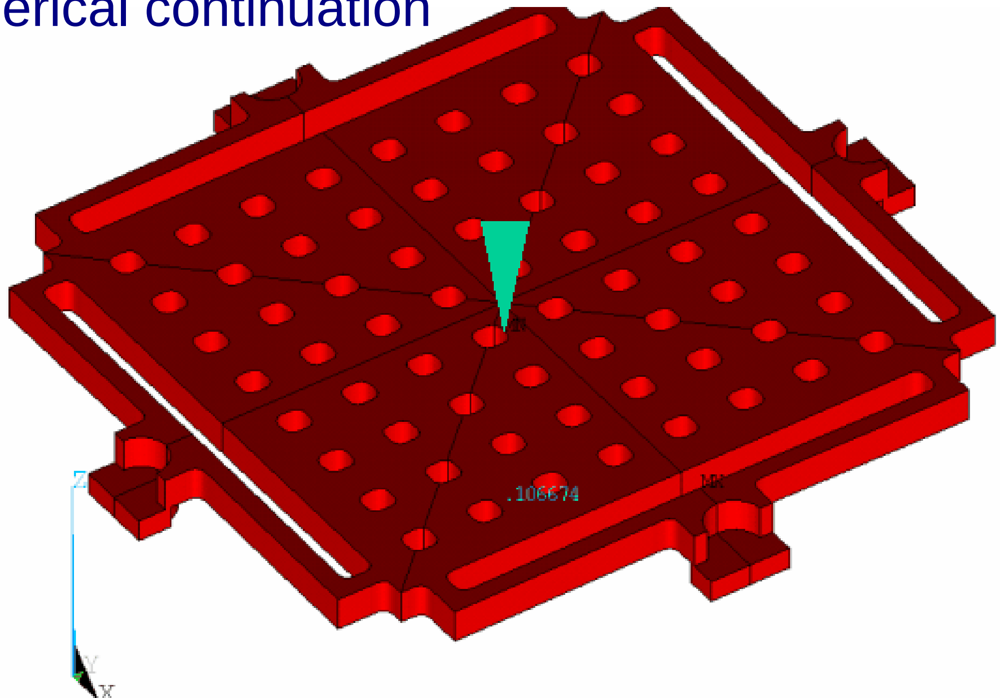
Solving Pull-in instability: DIPIE+

Finite Element implementation DIPIE+ to find static CV-curve:

- Consider <u>every</u> node to prescribe UZ displacement
- Search for voltage for which reaction force vanishes
- Node selection based on largest electrostatic pressure increment

Even better: Numerical continuation

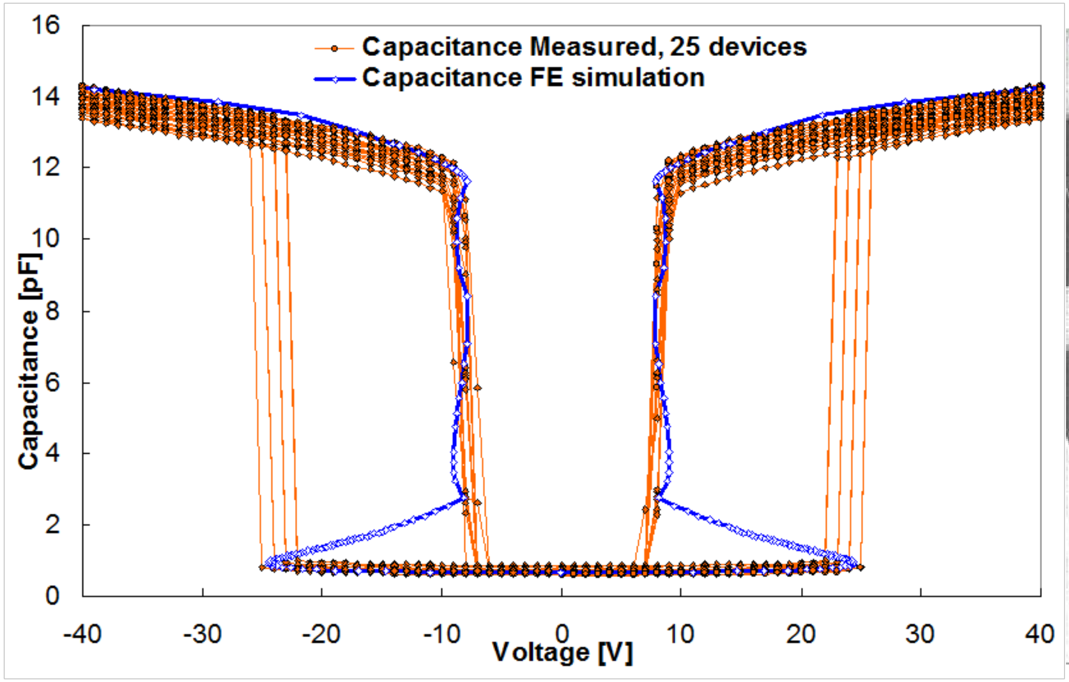


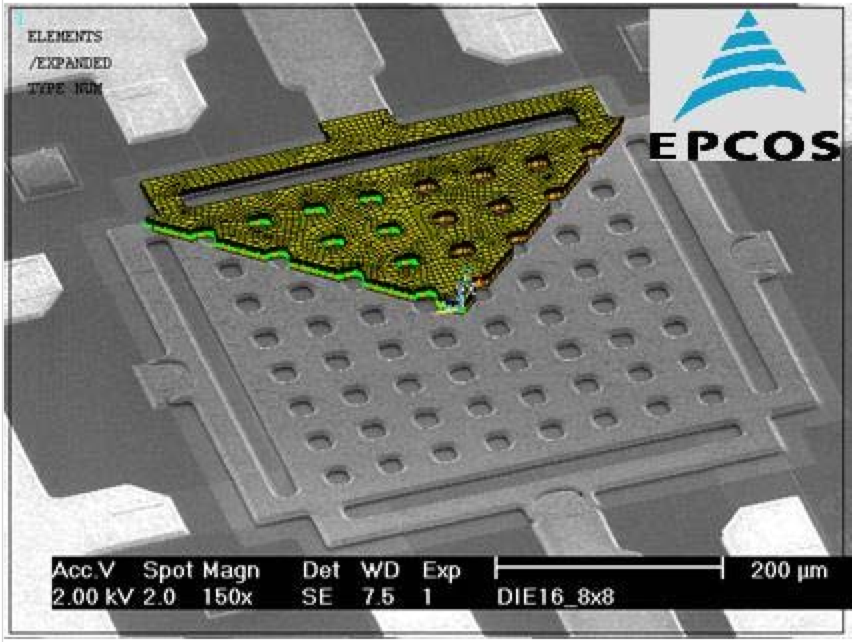


= prescribed displacement

Multi-physics model: Validation of static solution

- Good agreement between measured and predicted CV curves
- Slope in closed state capacitance is important feature, caused by surface roughness of the contact

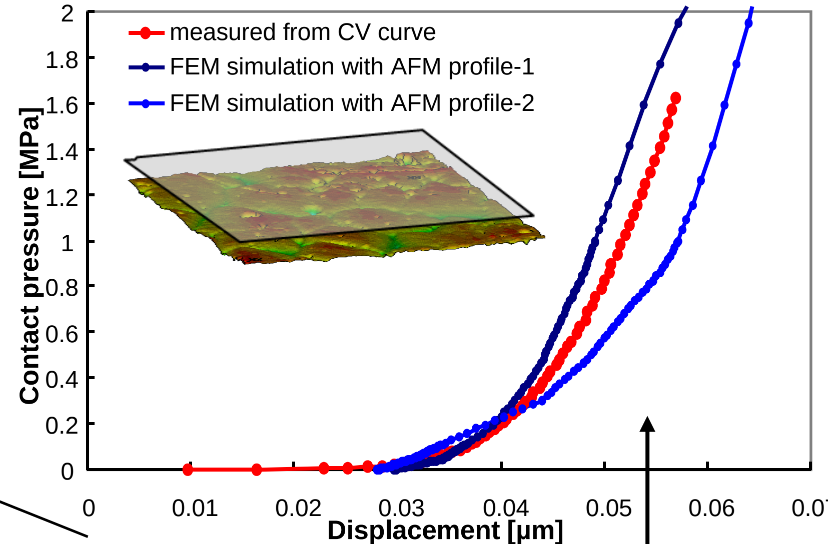


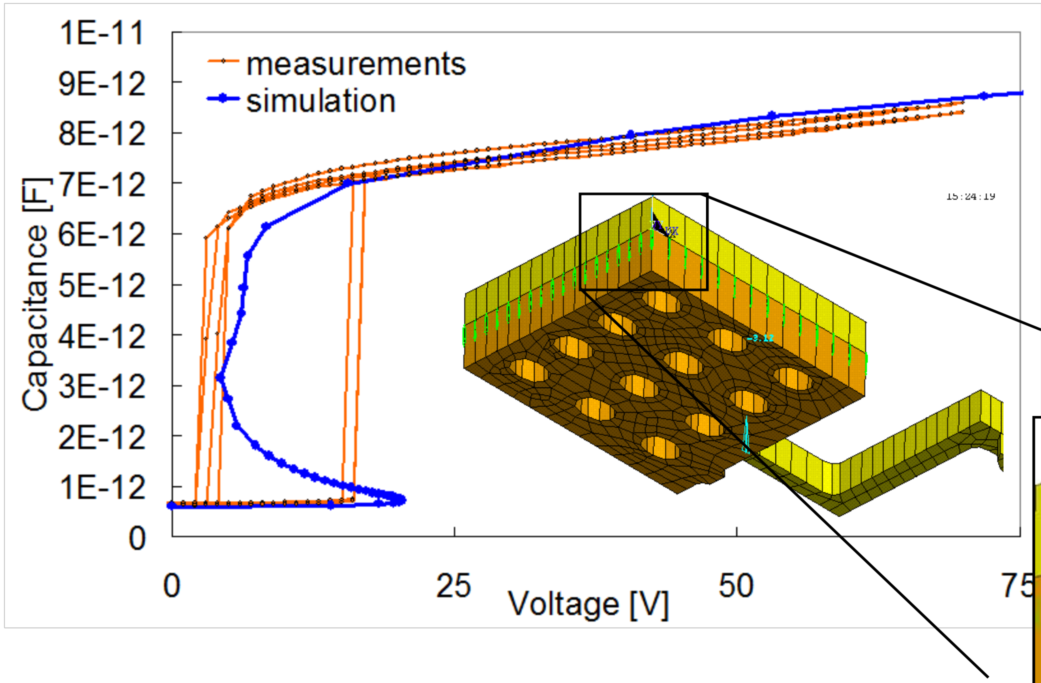


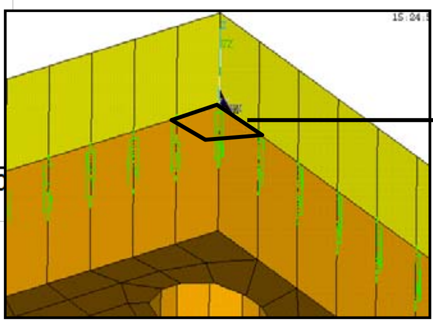
Non-linear Contact model

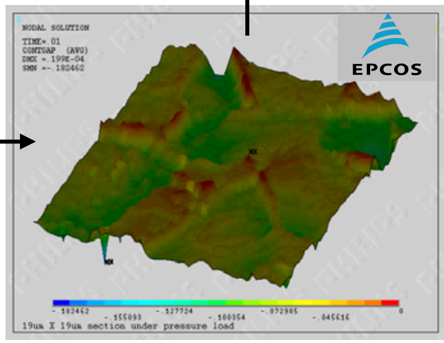
Surface roughness is homogenized in non-linear contact model:

- Contact behavior pressure(displacement) can be extracted from CV curve
- Simulation of contact pressure-displacement using imported AFM profiles
- Exponential function (I.e. Greenwood model)
- Multi-linear approximation in gasket element









Squeeze film theory

Implementation of new squeeze film element in Ansys:

- structural DOF's added to squeeze film element to create a **directly coupled fluid-structural element**
- Isothermal **non-linear compressible Reynolds equation** (because of large pressure changes when closing):

$$\frac{H}{p}\frac{\partial p}{\partial t}+\frac{\partial H}{\partial t}=\frac{H^3}{p12\mu}\left(\left(\frac{\partial p}{\partial x}\right)^2+\left(\frac{\partial p}{\partial y}\right)^2\right)+\frac{H^3}{12\mu}\nabla^2 p$$

- Rarefied gas effects taken into account by an effective viscosity (with optional accommodation factors) as proposed by Veijola:
  - Diffuse reflection:

$$\mu_{eff}=\frac{\mu}{1+9.638\cdot\left(\frac{L0\cdot P_{L0}}{p\cdot H}\right)^{1.159}}$$

$$Kn=\frac{L0\cdot P_{L0}}{p\cdot H}$$

H=gap height (=Gap0-UZ) structural DOF

p=Pressure (DOF)

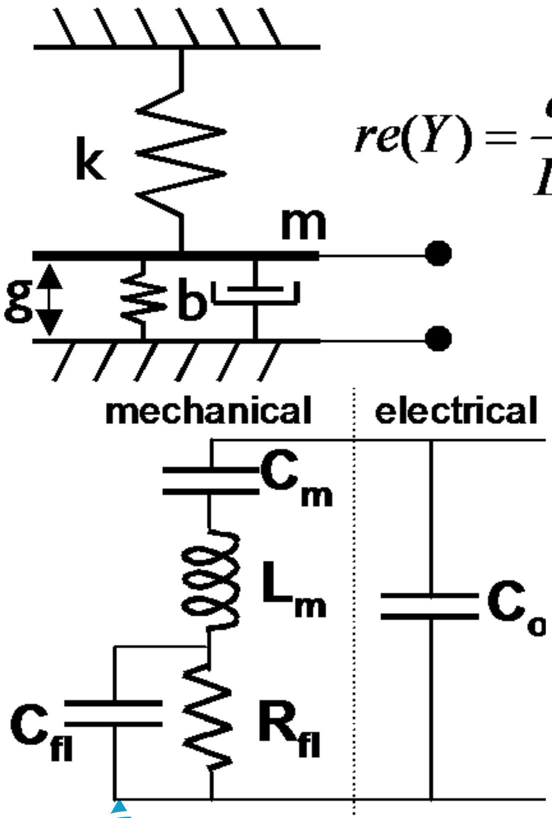
L0=molecular mean free path at P_{L0}

μ=viscosity

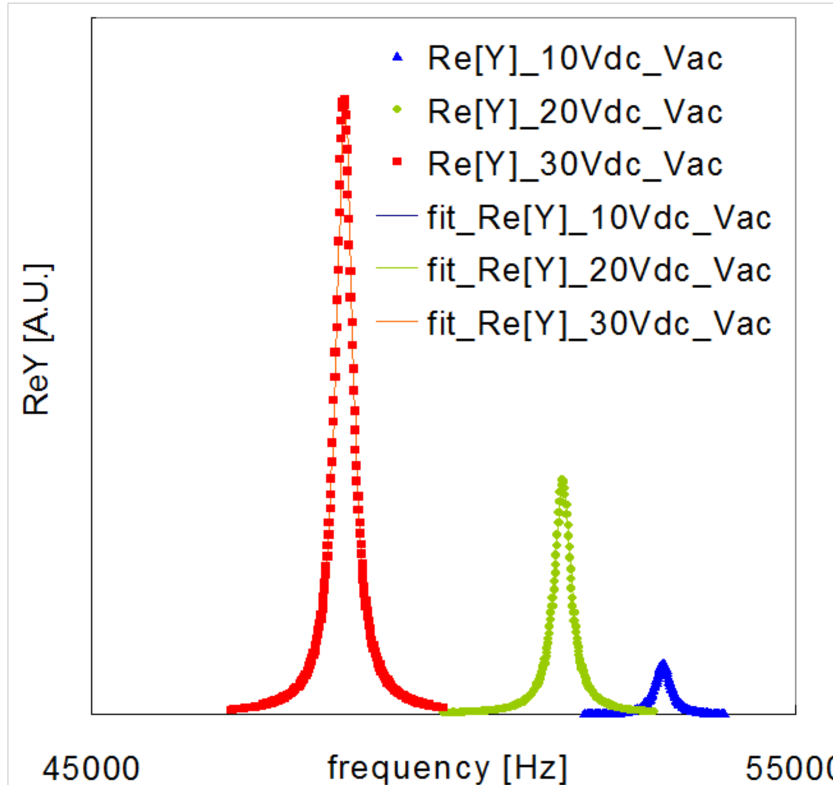
Kn= Knudsen number

Effective viscosity extracted from measurements

- Impedance analyzer or LCR meter used to measure Re[Y]
- Parasitic shunt branch de-embedded before fitting mechanical Q-factor
- In vacuum chamber to vary ambient pressure

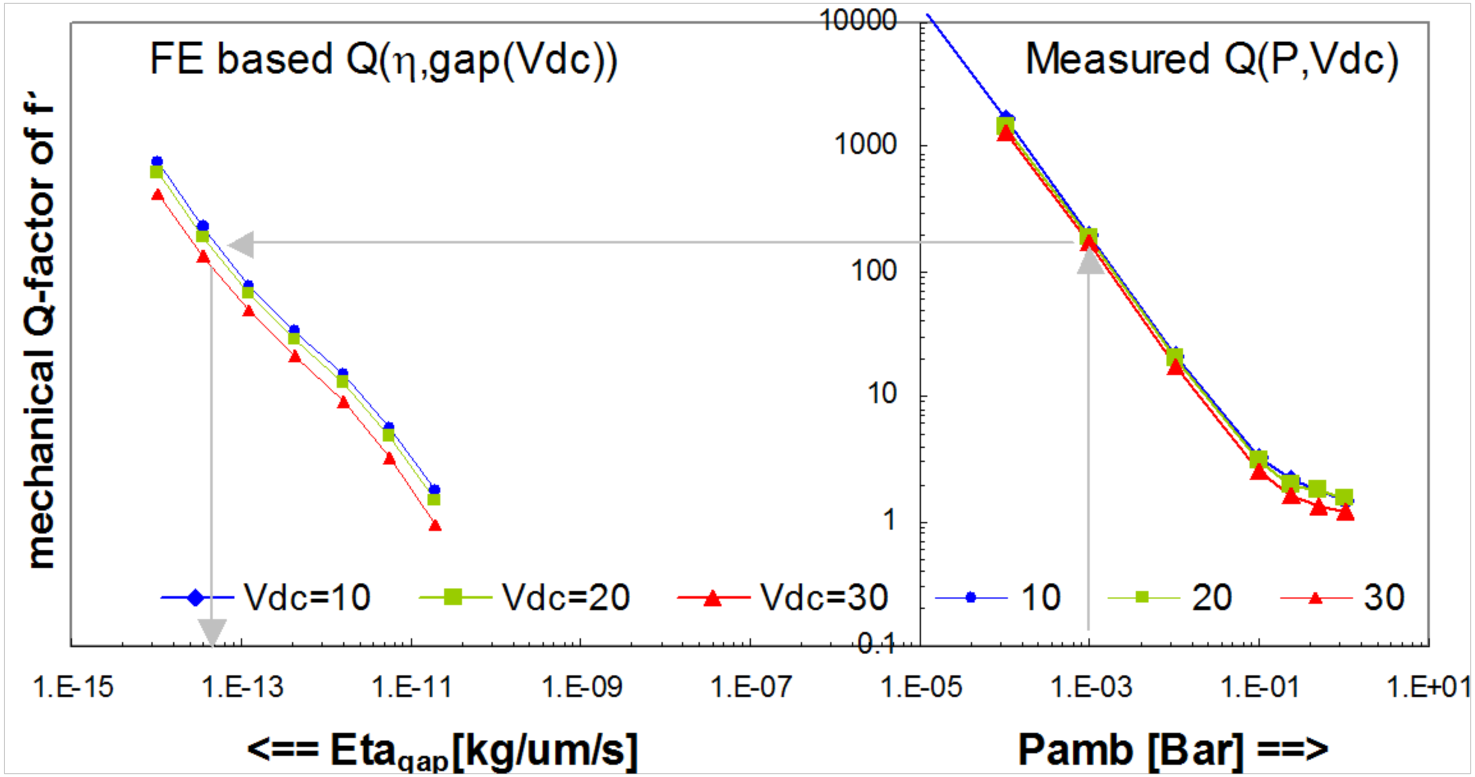


$$re(Y) = \frac{\omega}{L_m}\,\frac{\dfrac{\omega\,\omega_0}{Q}}{\dfrac{\omega^2\,\omega_0^2}{Q^2}+\left(\omega^2-\omega_0^2\right)^2}$$



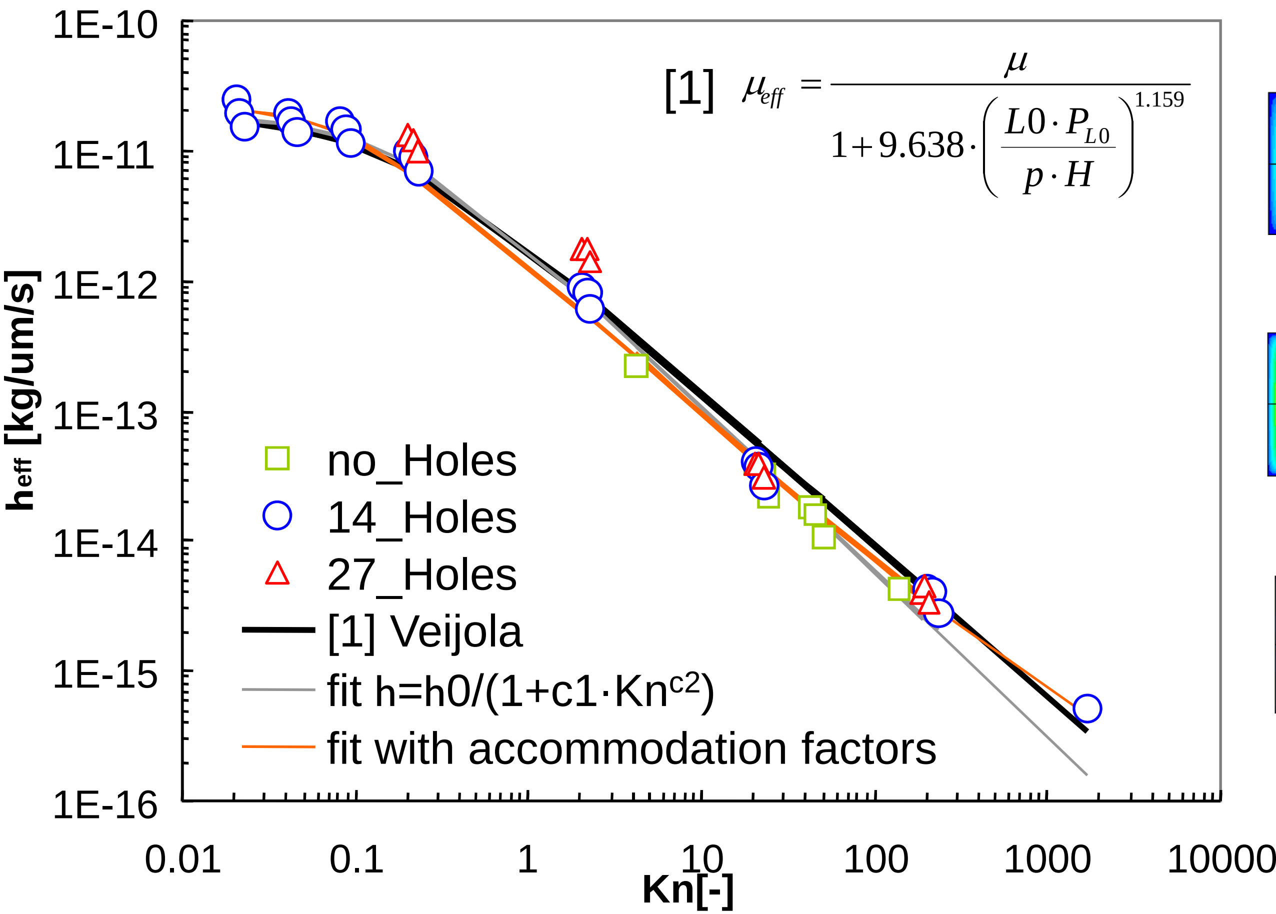
Effective viscosity extracted from measurements

- Measure Q-factor for various designs, bias voltage & pressure range
- Simulate Q-factor's dependency on viscosity & bias voltage
  - Q-factor insensitive to exact match of first eigenfrequency

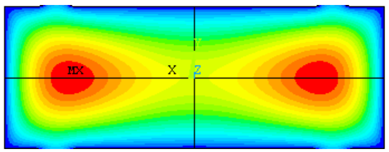


Effective viscosity from measurements

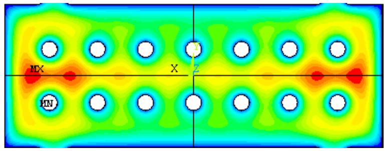
- Small deviation from Veijola
- Better fit obtained by introduction of accommodation factors



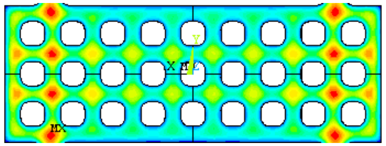
No holes



14 holes

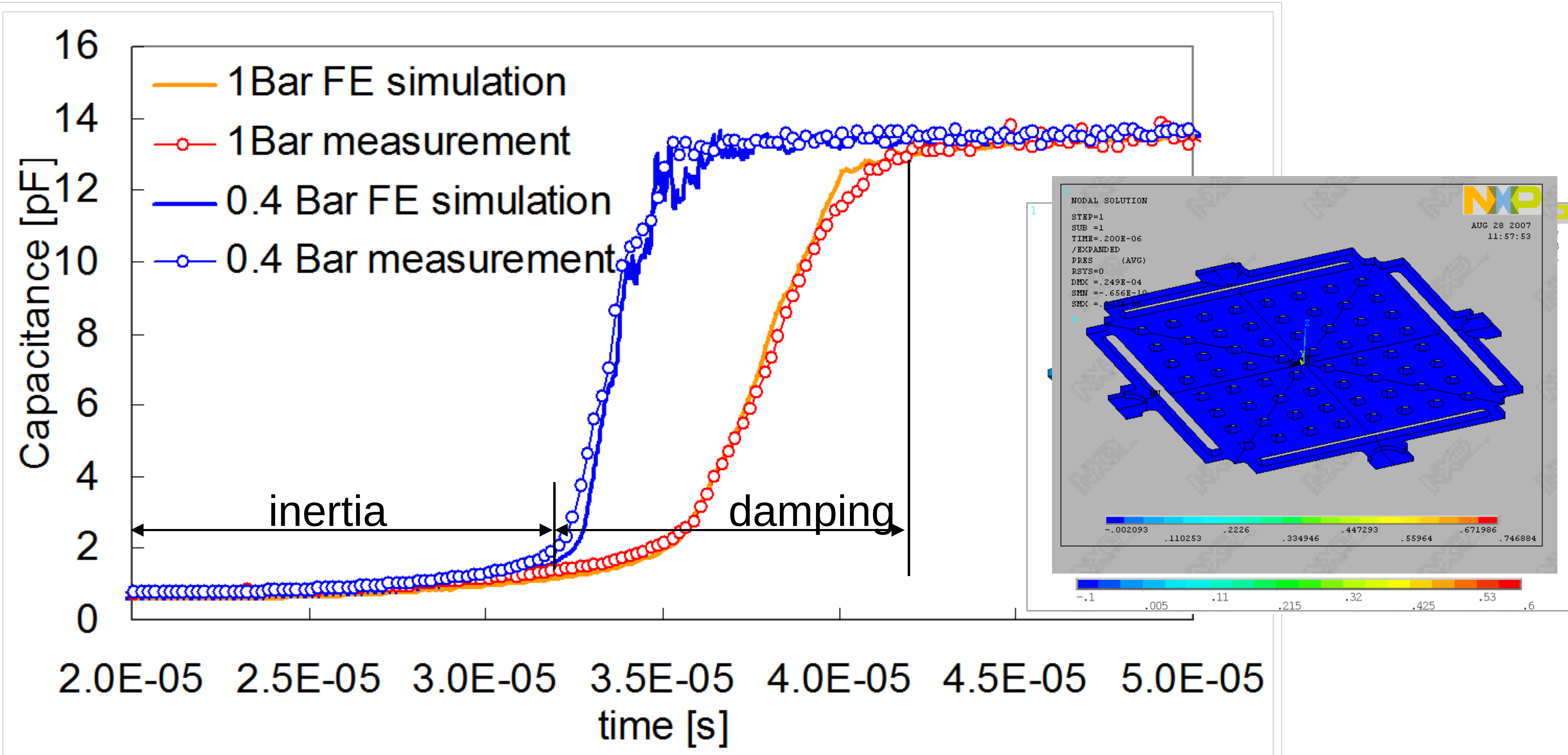


27 holes



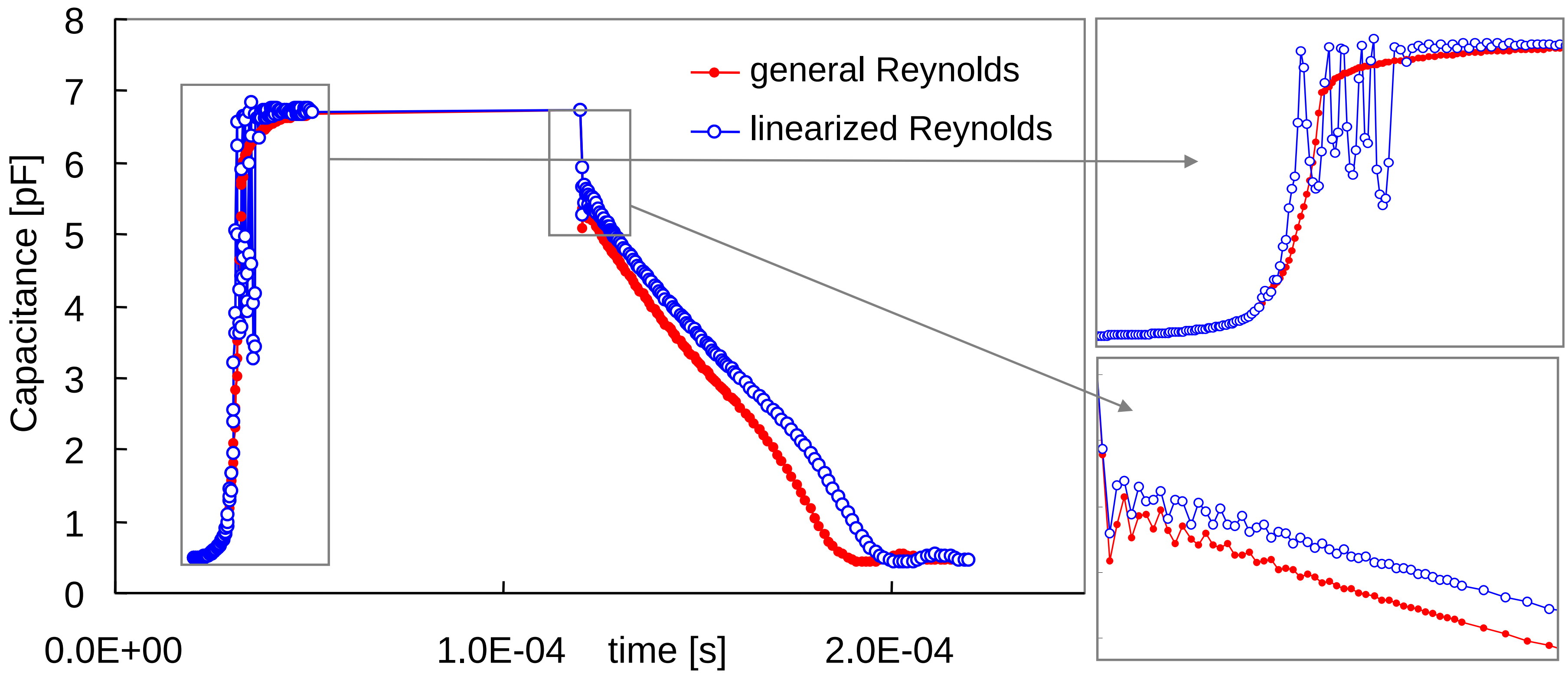
Close/opening transient results

- 8x8 40V open & close transient at 0.4bar & 1bar cavity pressure
- FE model includes initial stress derived from interferometer profiles



Linearized versus general Reynolds equation

- Significant difference between linearized & non-linear Reynolds
- Pressures clearly outside range for which linearization is valid



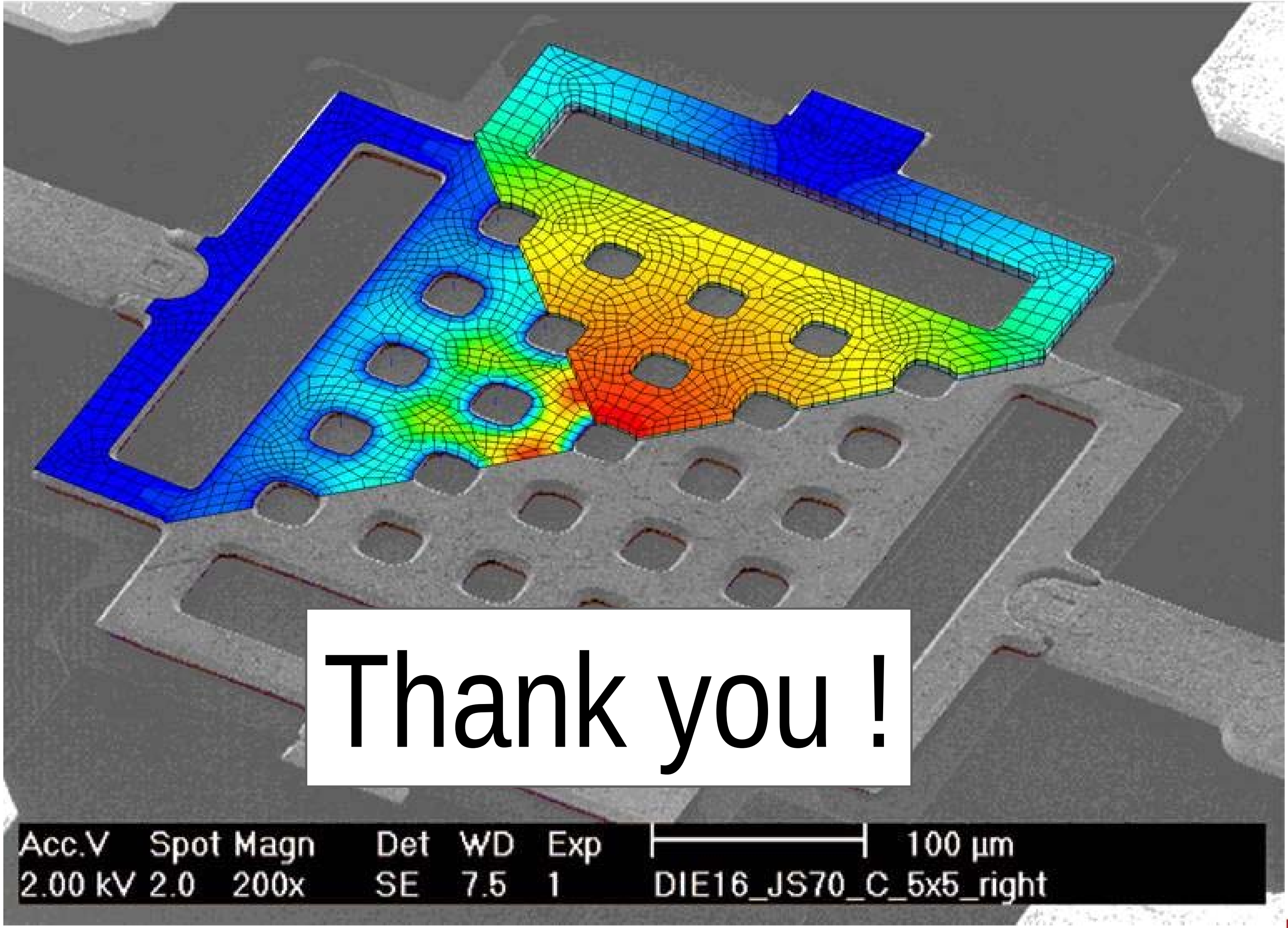
Conclusions

- Demonstrated an efficient finite element implementation & validation of squeeze film effects for prediction of transient response
- Rarefaction effects were quantified by extracting the effective viscosity from measurements
- Transient simulations show good agreement with measurements of closing and opening cycles
- Multiphysics simulation improves the design by reducing the opening and closing times for the capacitive switch
- Non-linear Reynolds equation must be used for this type of devices

Outlook

2020? This is what we‘d like to have tomorrow:

- Advanced non-linear multi-physics solver to handle snap-backs:
  - Numerical-continuation e.g. Arc-length for multi-physics
- Non-linear materials in transient with acceptable run-times
  - Multi-size, multi-time scale solution
- More multi-physics domains for reliability assessments:
  - Charge diffusion for dielectric charging (specific for this MEMS)
  - HF-Electro Magnetic to predict power dissipation & temperature
  - Strain gradient crystal plasticity model (adds 18 DOF’s) to handle size effects in materials (general for MEMS & NEMS)
- Integration of FE results in system/circuit simulation:
  - Predict large signal system performance (e.g. ACPR) with e.g. harmonic balance


Acc.V Spot Magn Det WD Exp
100 µm
2.00 kV 2.0 200x SE 7.5 1 DIE16_JS70_C_5x5_right

Thank you !