PAUL SCHERRER INSTITUT

PSI

Lothar Holitzner :: Designing Engineer :: Paul Scherrer Institut

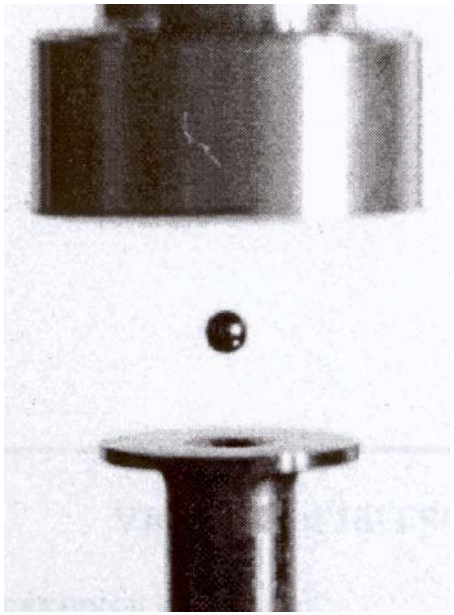
Acoustic Upside-down Levitator with a Solid Sample

24.10.2018

COMSOL CONFERENCE 2018 LAUSANNE

Introduction: What is Acoustic Levitation?

An example

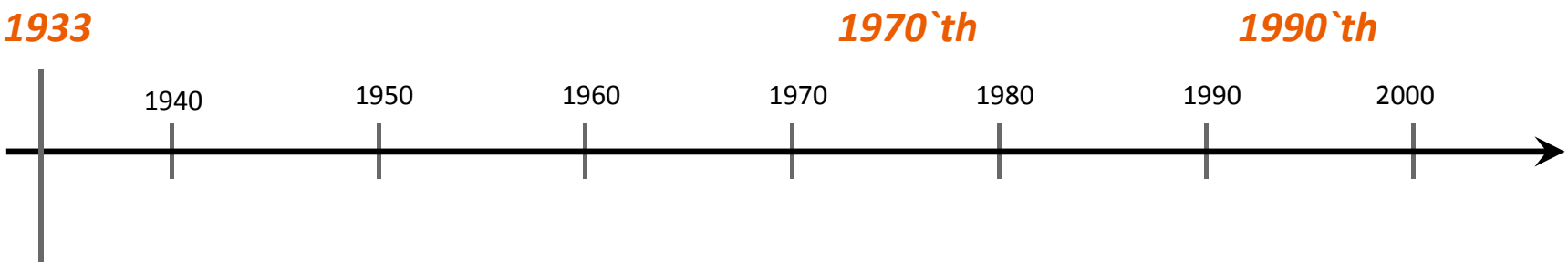


2 mm steel sphere free levitating in an acoustic 58 kHz levitator /4/

/4/ A. Schnitzler, Aufbau einer akustischen Falle, Joh. Gutenb.-Uni.Mainz, 1998

Fields of Application

History



Karl Bücks, Hans Müller, Zeitschrift für Physik (1933), Breslau. /5/

Description of the phenomenon

Space applications (by NASA and ESA)

material, physical and biological experiments

micro gravitation, „containerless processing“

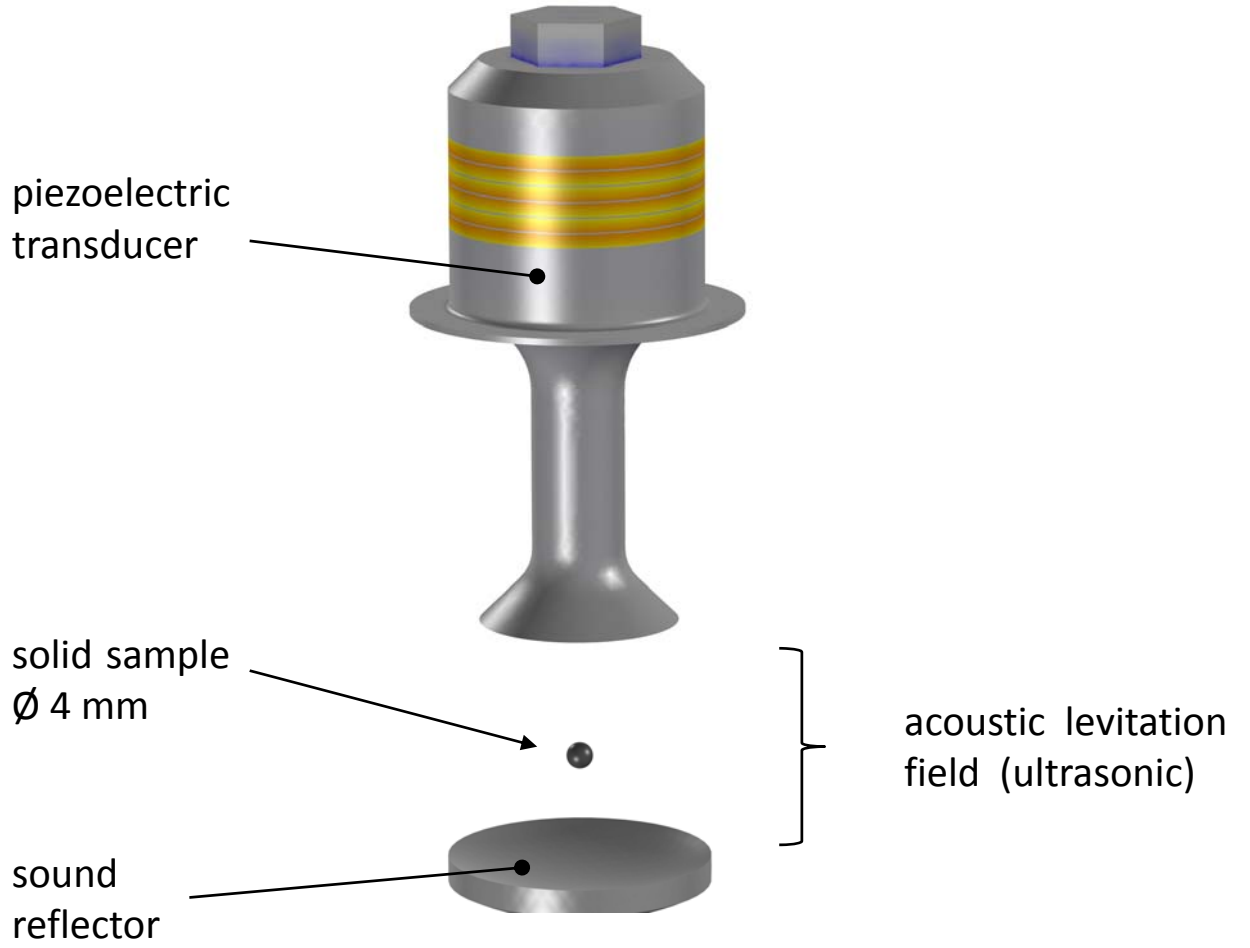
Terrestrial appl.

meteorologic, chemical, medical, ...

/5/ Bücks, K. & Müller, H. Z. Physik (1933) 84: 75. https://doi.org/10.1007/BF01330275

The Model

Acoustic Upside-down Levitator with a Solid Sample



Model Development Steps: To-do List

1. Assemble the transducer
   (Stationary study, prestressed)
2. Find the transducer geometry
   (Eigenfrequency study)
3. Vibrate the prestressed transducer
   (Frequency domain study)
4. Inspect the transducer motion
   (Time dependent study)
5. Scan the sample position
   (Frequency domain study)
6. Calculate the sample force balance
   (Frequency domain study)

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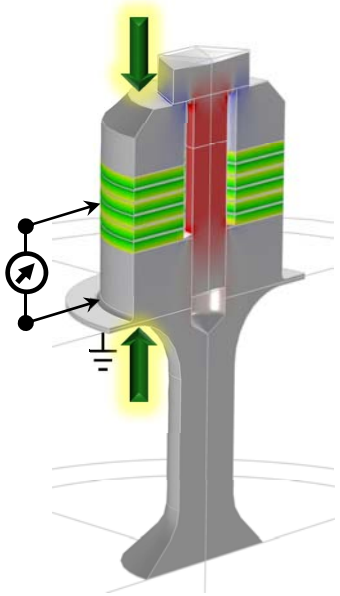

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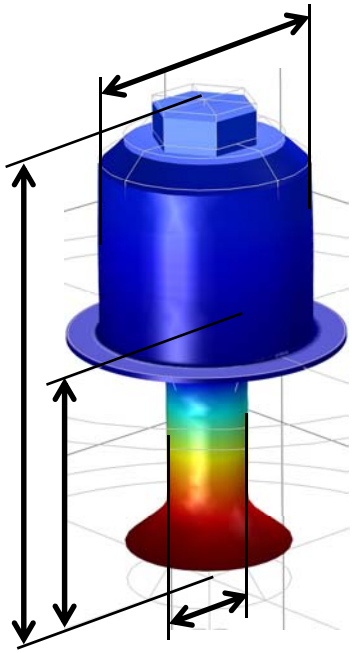

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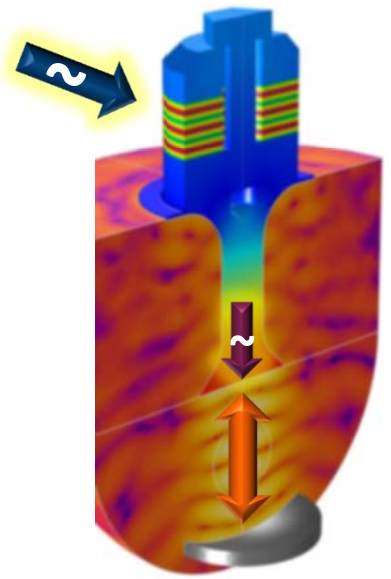

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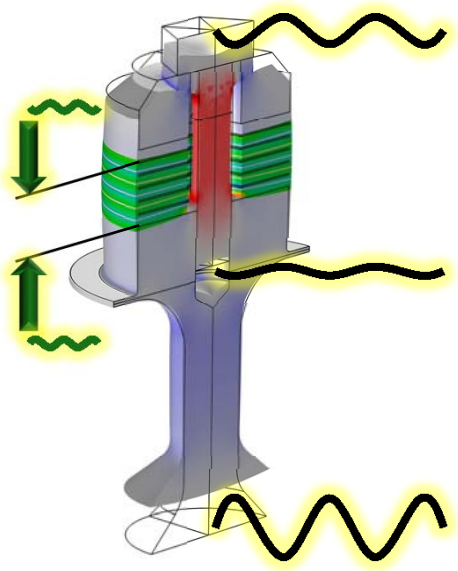

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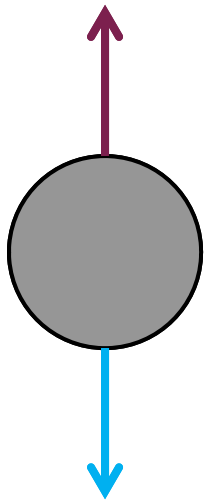
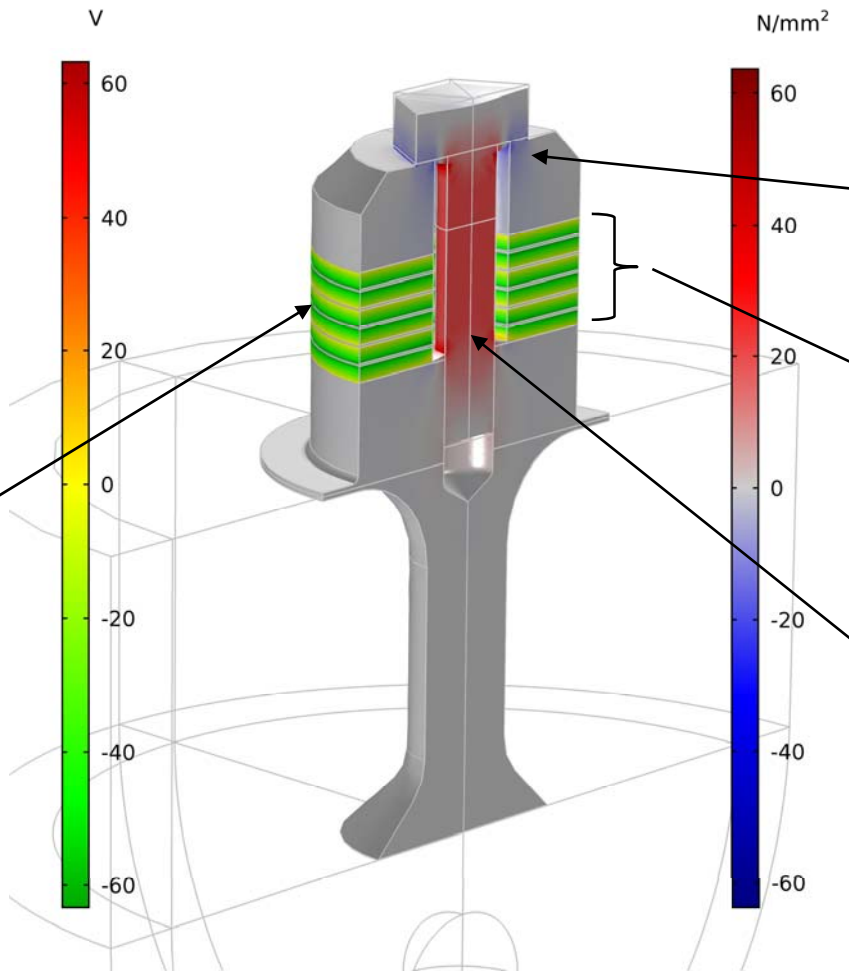


Model Development: Study 1

Piezo preload (Stationary, prestressed)



resulting
piezo voltage
(Floating Potential)

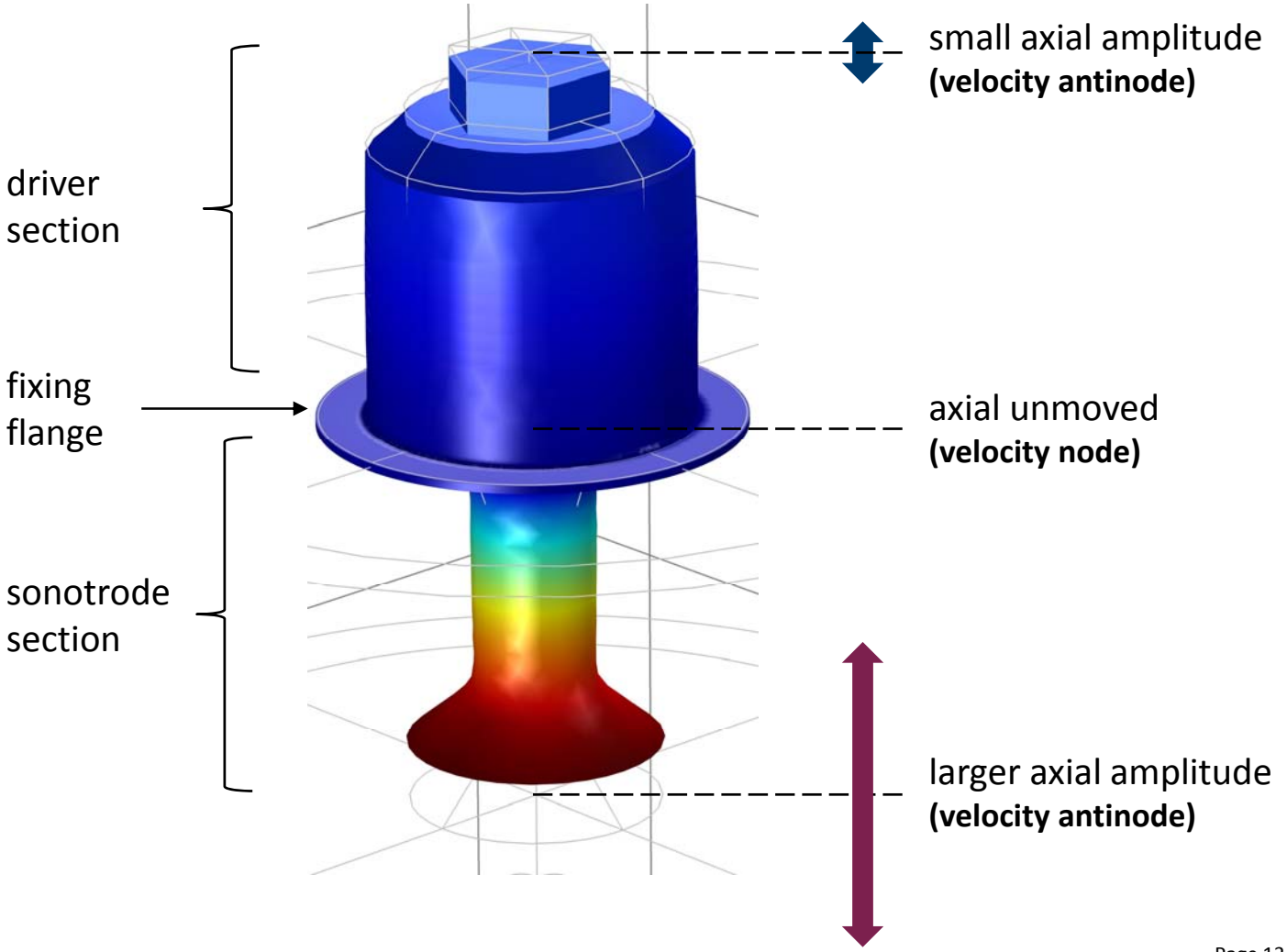
compressive stress
(blue region)
below screw head

axially compressed
stack of piezo rings

bolt under
pre-tension

Model Development: Study 2

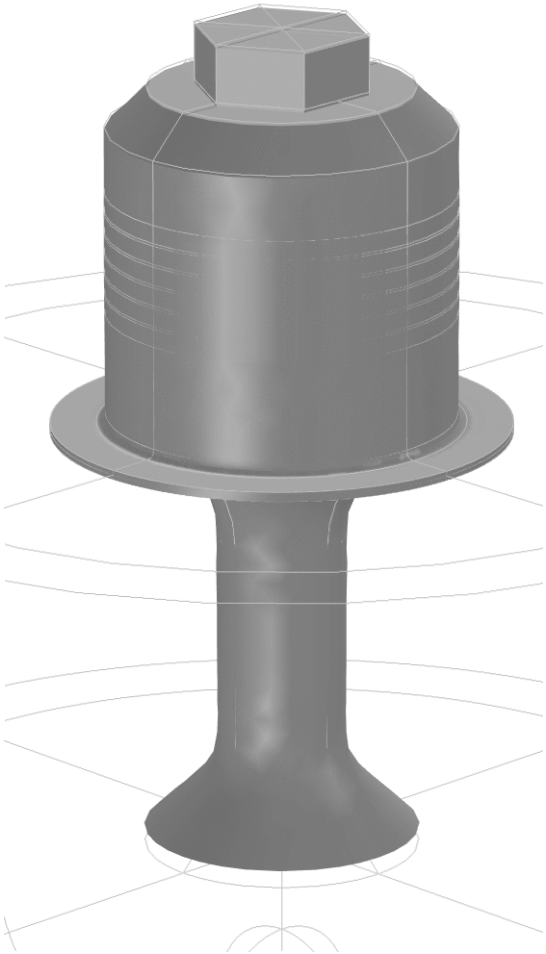
Transducer geometry (Eigenfrequency, prestressed)



Model Development: Study 2

Transducer geometry (Eigenfrequency, prestressed)

Transducer Eigenfrequency
22002 Hz



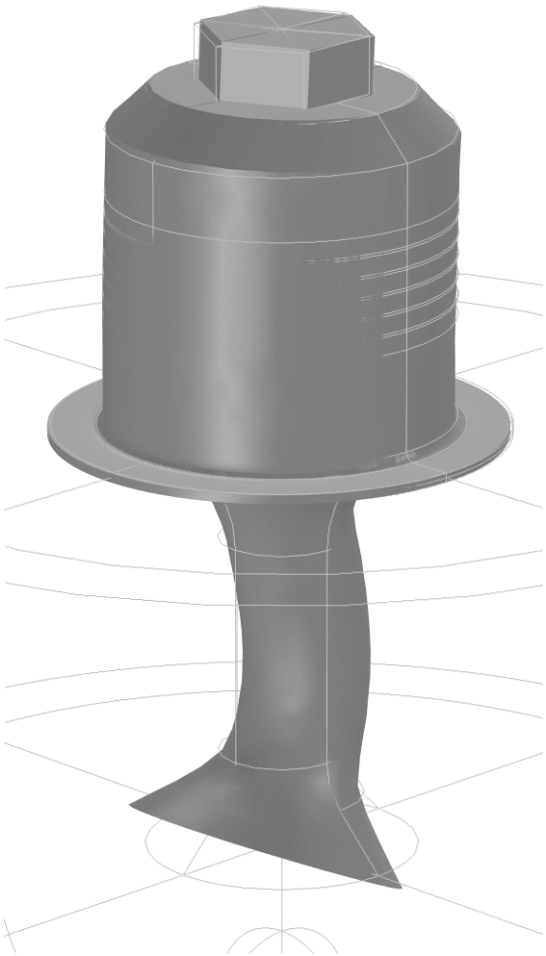
Deformation with scale factor 130

Model Development: Study 2

Transducer geometry (Eigenfrequency, prestressed)

Example:

Undesired
Eigenfrequency
19963 Hz

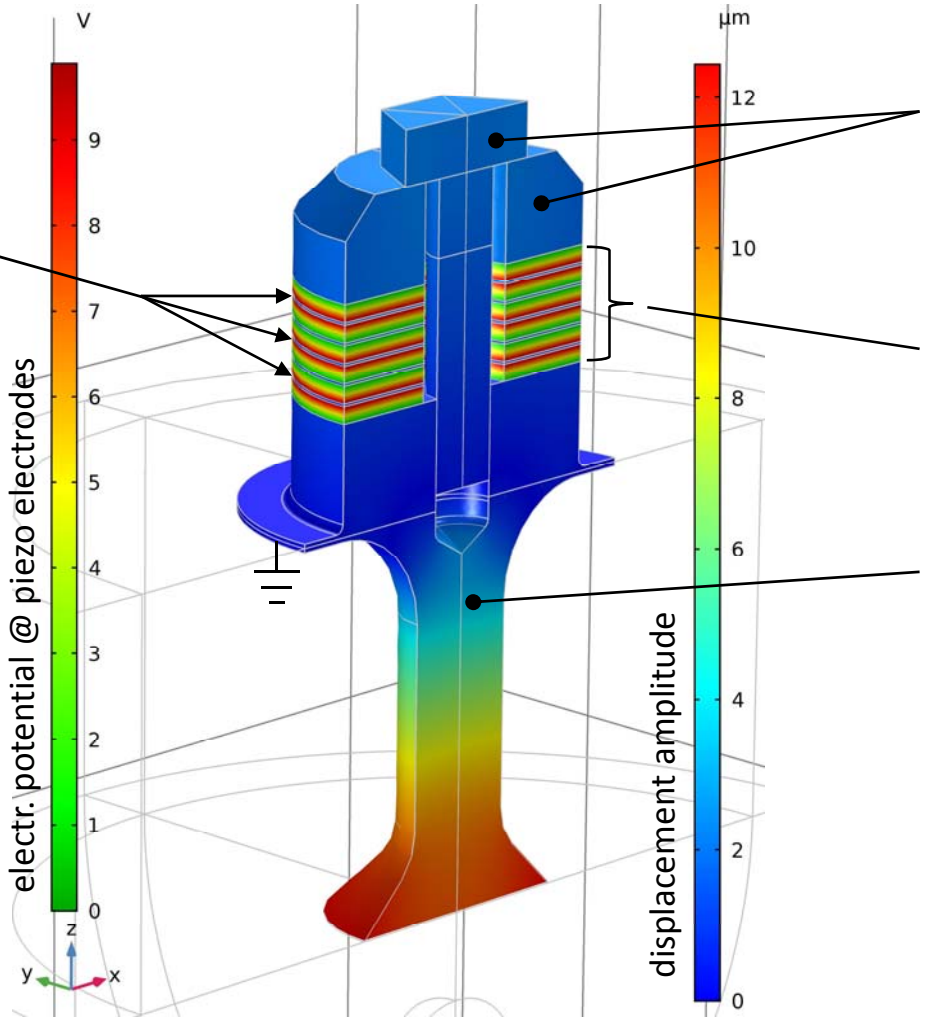


Deformation with
scale factor 130

Model Development: Study 3

Frequency scan (Frequency Domain, prestressed)

AC voltage at piezo electrodes (*Harmonic Pertubation*)



stainless steel (1.4435)

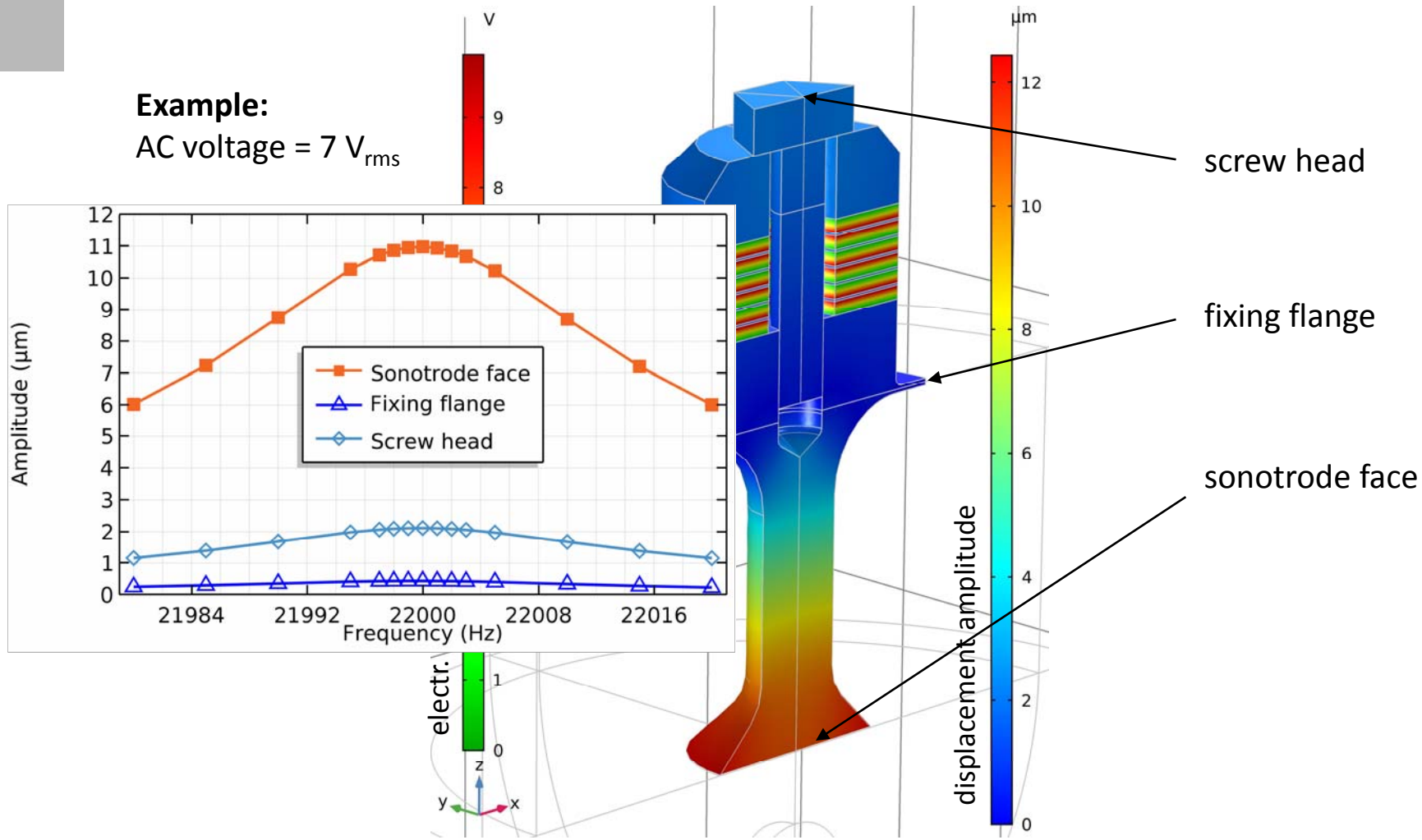
PZT-4

Ti6Al4V (3.7165) material damping with quality factor Q = 1500

Model Development: Study 3

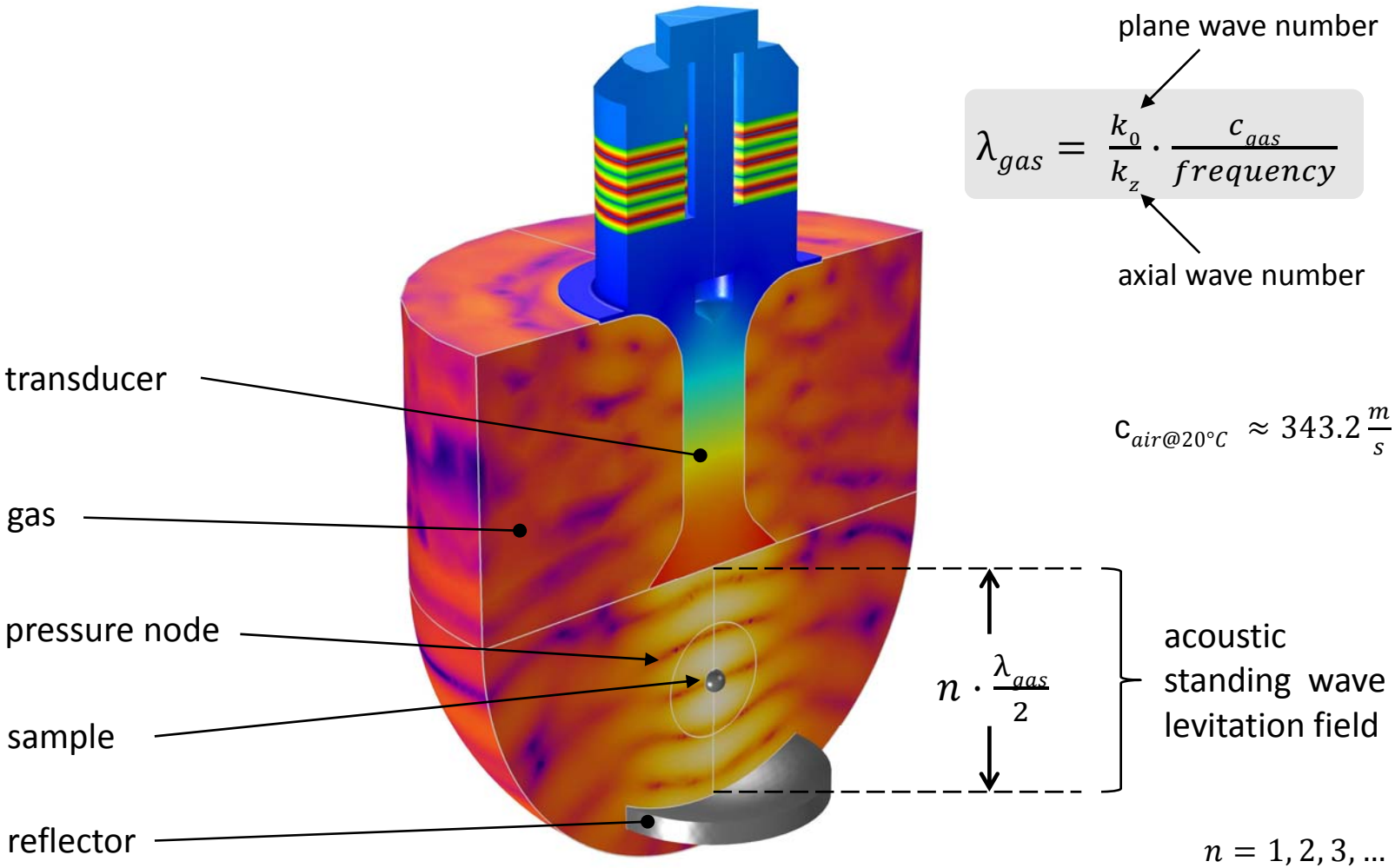
Frequency scan (Frequency Domain, prestressed)

Example:
AC voltage = 7 V_{rms}



Model Development: Study 3

Frequency scan (Frequency Domain, prestressed)

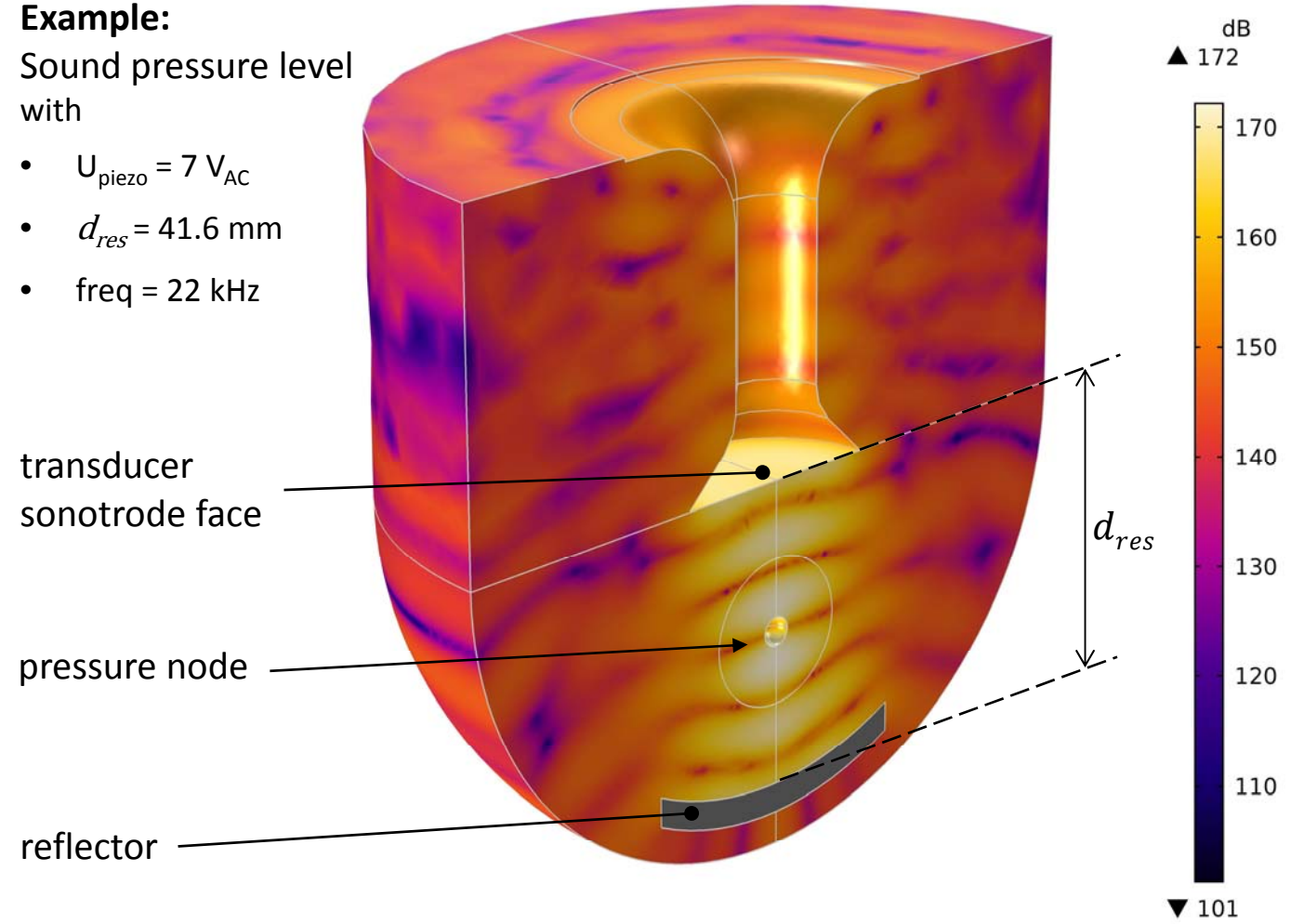


Model Development: Study 3

Frequency scan (Frequency Domain, prestressed)

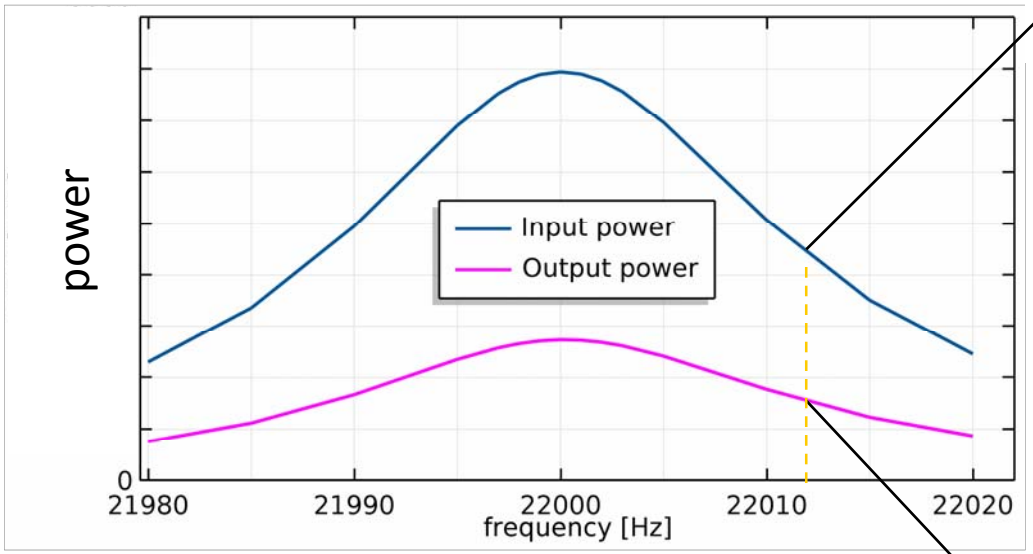
Example:
Sound pressure level
with

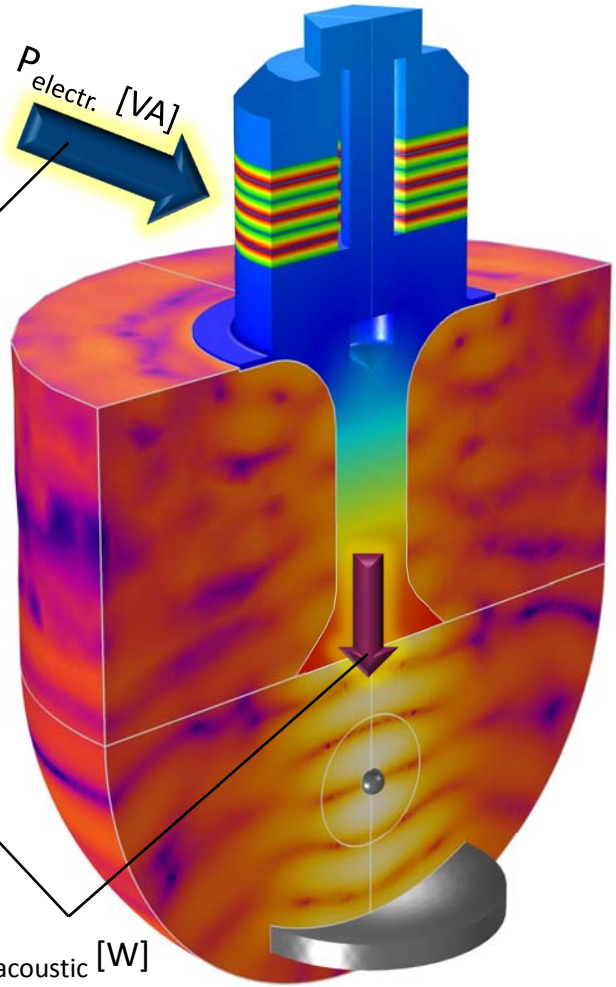
- U_{piezo} = 7 V_{AC}
- d_{res} = 41.6 mm
- freq = 22 kHz



Model Development: Study 3

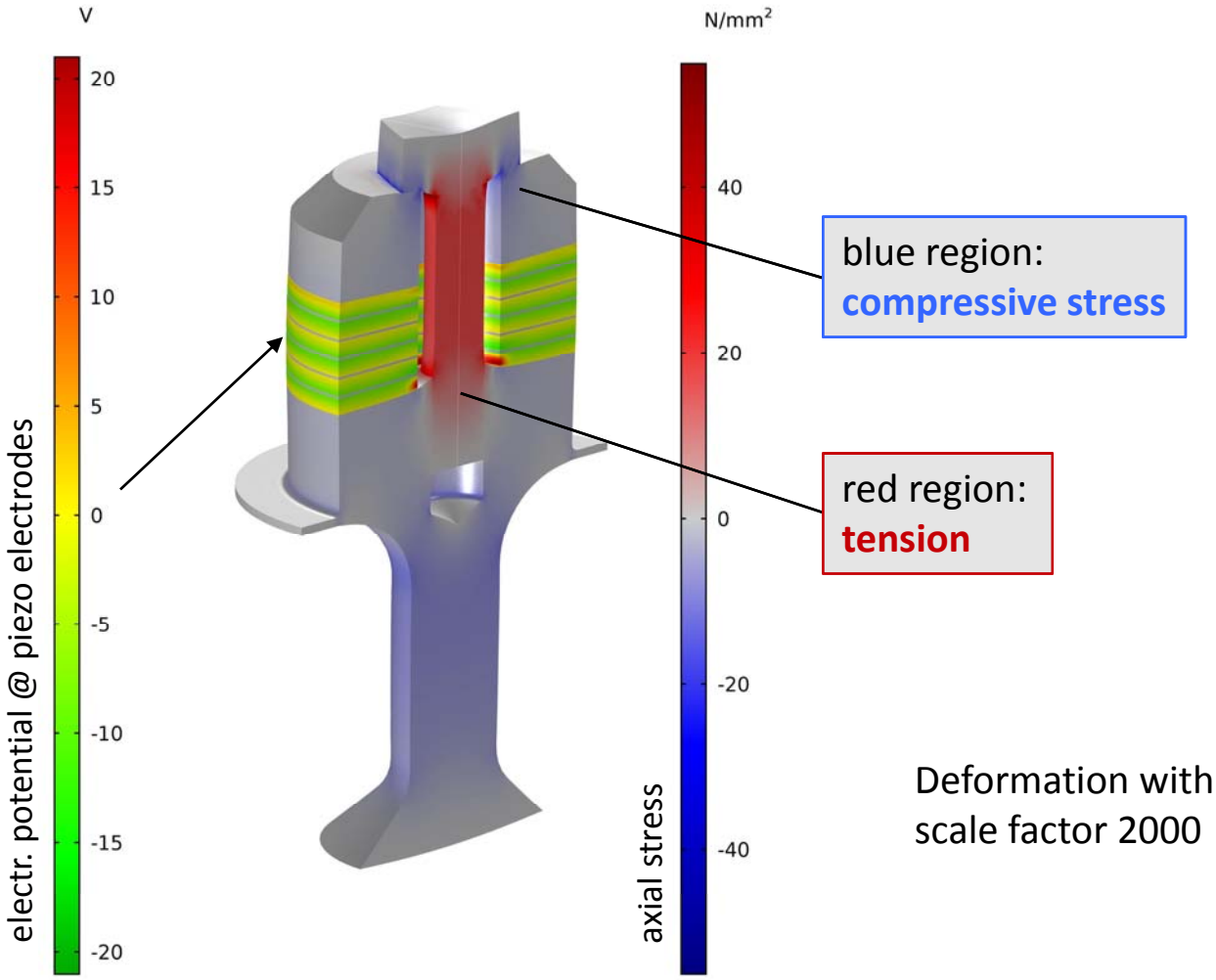
Frequency scan (Frequency Domain, prestressed)





Model Development: Study 4

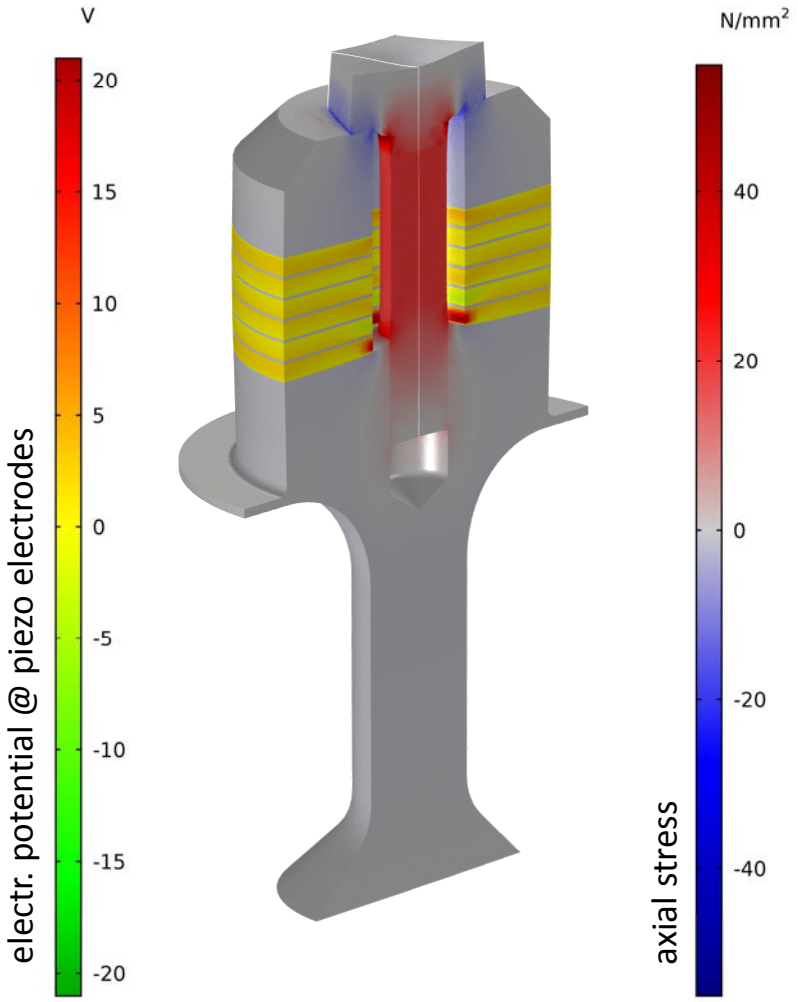
Transducer motion (Time Dependent, prestressed)



Deformation with scale factor 2000

Model Development: Study 4

Transducer motion (Time Dependent, prestressed)



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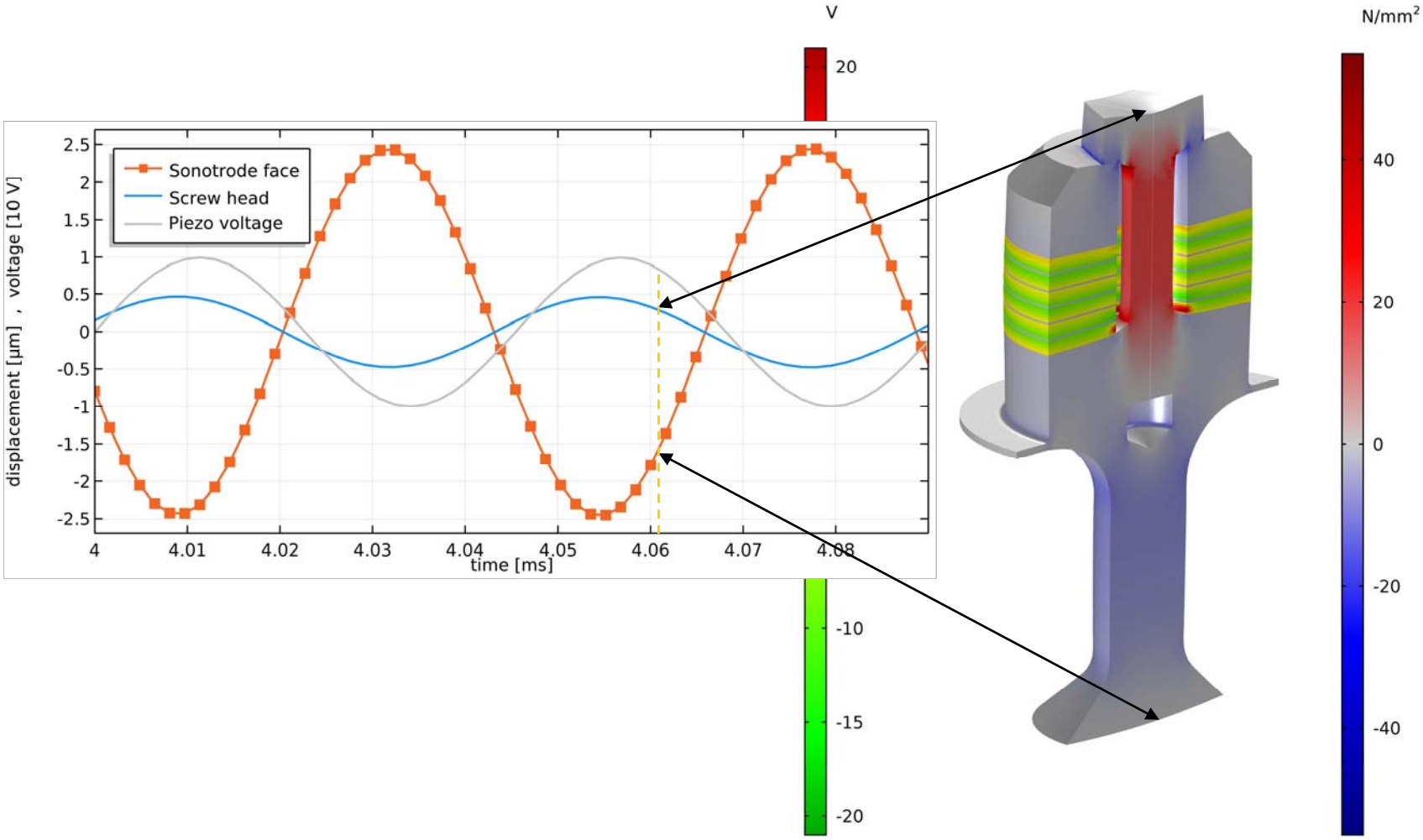
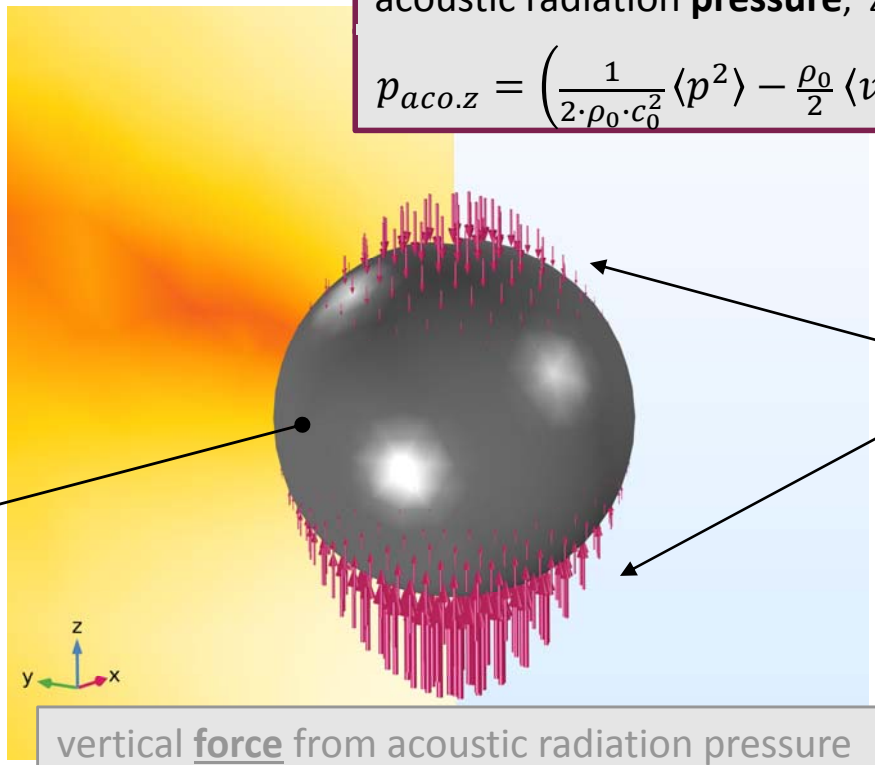


Model Development: Study 5

Acoustic levitation force progression (Frequency Domain, prestressed)

acoustic radiation **pressure**, z-component

$$p_{aco.z} = \left(\frac{1}{2 \cdot \rho_0 \cdot c_0^2}\langle p^2\rangle - \frac{\rho_0}{2}\langle v^2\rangle\right) \cdot n_z + \rho_0 \langle v_n \cdot v_z\rangle$$



solid sample

acoustic radiation pressure z-component

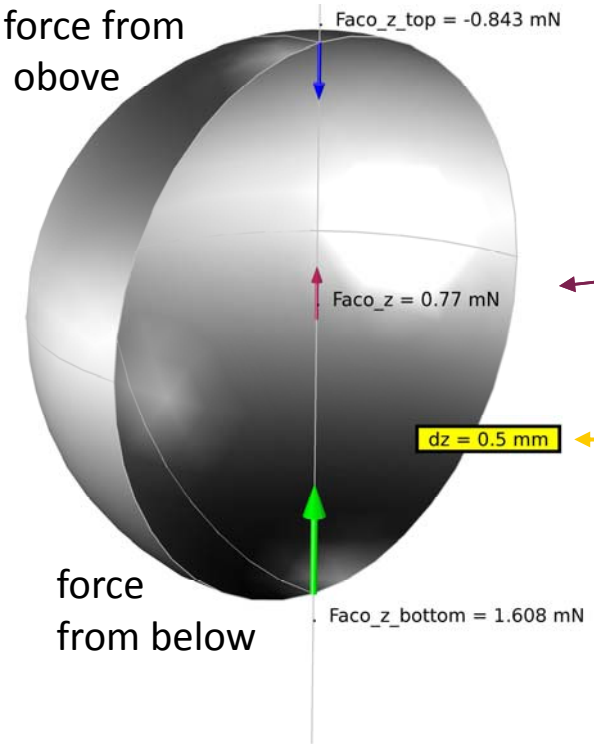
vertical **force** from acoustic radiation pressure

$$F_{aco.z} = -\int_{S_{sample}} \left(\left(\frac{1}{2 \cdot \rho_0 \cdot c_0^2}\langle p^2\rangle - \frac{\rho_0}{2}\langle v^2\rangle\right) \cdot n_z + \rho_0 \langle v_n \cdot v_z\rangle\right) da$$

Model Development: Study 5

Acoustic levitation force progression (Frequency Domain, prestressed)

force from above



force from below

resulting force from acoustic radiation pressure

$$F_{aco.z} = F_{aco.z.bottom} + F_{aco.z.top}$$

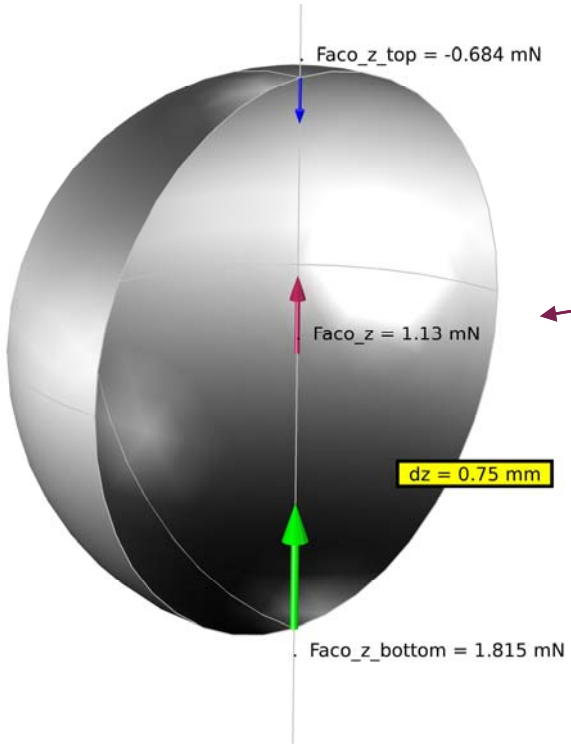
vertical distance below sound field pressure node

vertical **force** from acoustic radiation pressure

$$F_{aco.z} = -\int_{S_{sample}} \left(\left(\frac{1}{2 \cdot \rho_0 \cdot c_0^2} \langle p^2 \rangle - \frac{\rho_0}{2} \langle v^2 \rangle \right) \cdot n_z + \rho_0 \langle v_n \cdot v_z \rangle \right) da$$

Model Development: Study 5

Acoustic levitation force progression (Frequency Domain, prestressed)



resulting force from acoustic radiation pressure

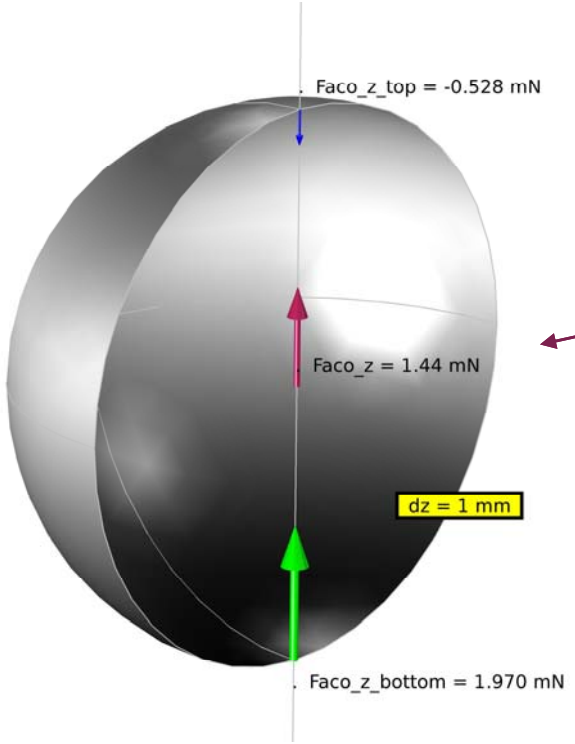
$F_{aco.z}$

vertical **force** from acoustic radiation pressure

$$F_{aco.z} = -\int_{S_{sample}} \left(\left(\frac{1}{2 \cdot \rho_0 \cdot c_0^2} \langle p^2 \rangle - \frac{\rho_0}{2} \langle v^2 \rangle \right) \cdot n_z + \rho_0 \langle v_n \cdot v_z \rangle \right) da$$

Model Development: Study 5

Acoustic levitation force progression (Frequency Domain, prestressed)



resulting force from acoustic radiation pressure

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vertical **force** from acoustic radiation pressure

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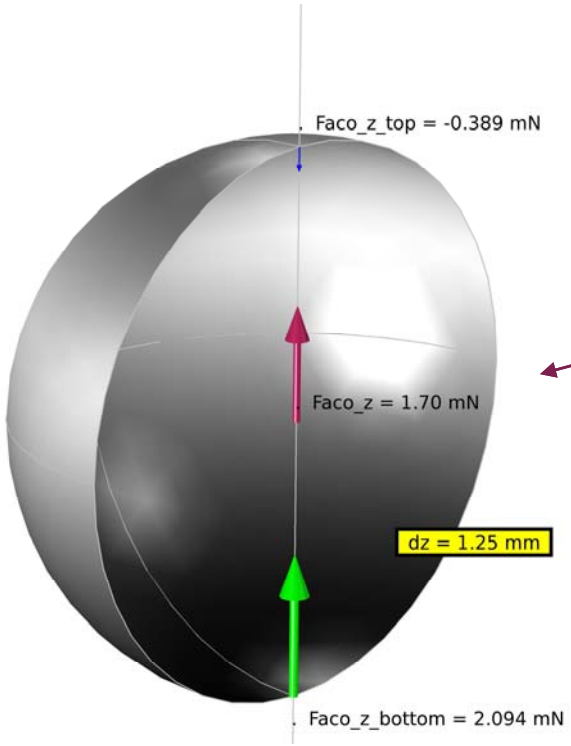
Model Development: Study 5

Acoustic levitation force progression (Frequency Domain, prestressed)



resulting force from acoustic radiation pressure

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vertical **force** from acoustic radiation pressure

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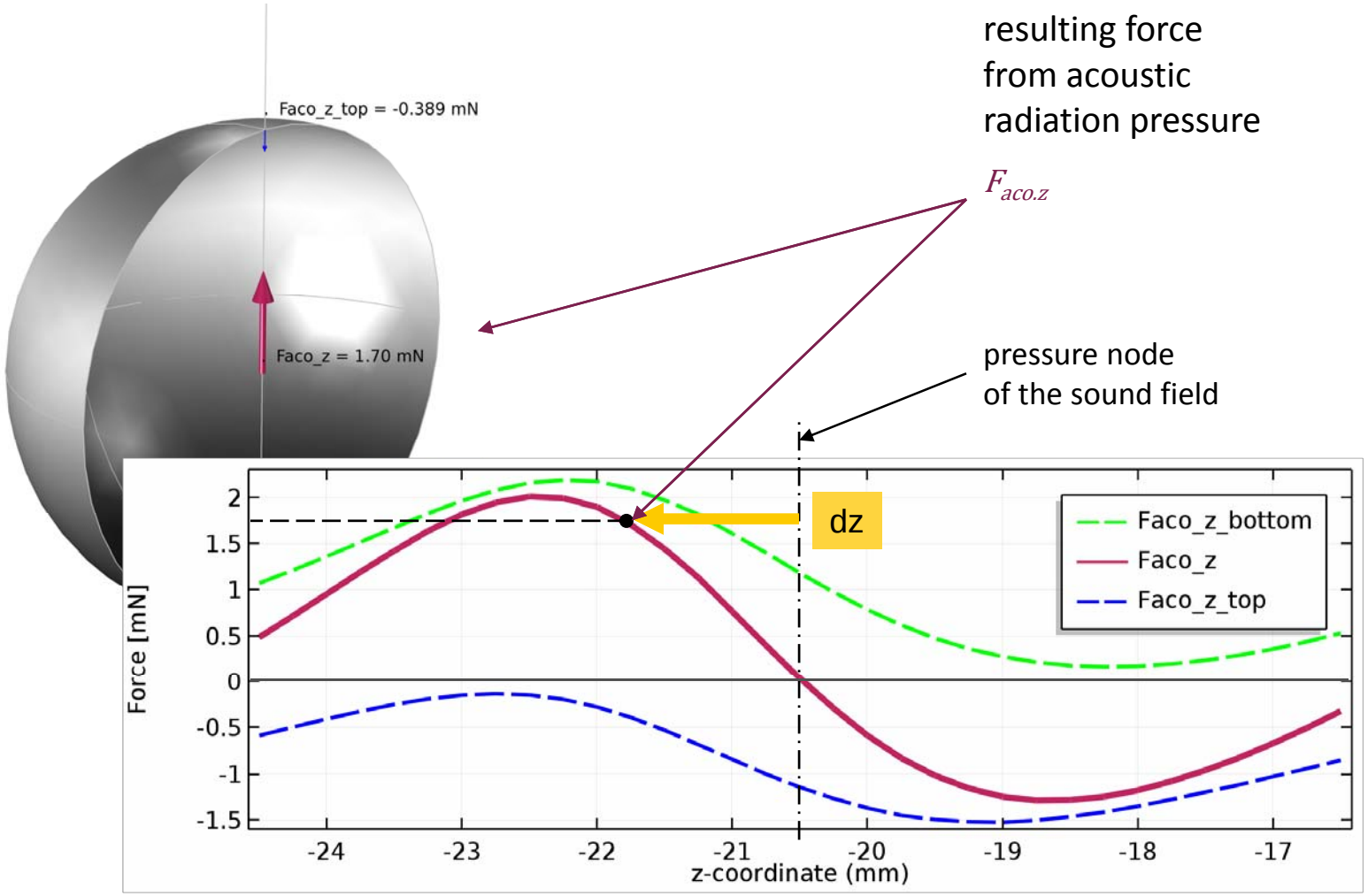
Model Development: Study 5

Acoustic levitation force progression (Frequency Domain, prestressed)

resulting force
from acoustic
radiation pressure

$F_{aco.z}$

pressure node
of the sound field



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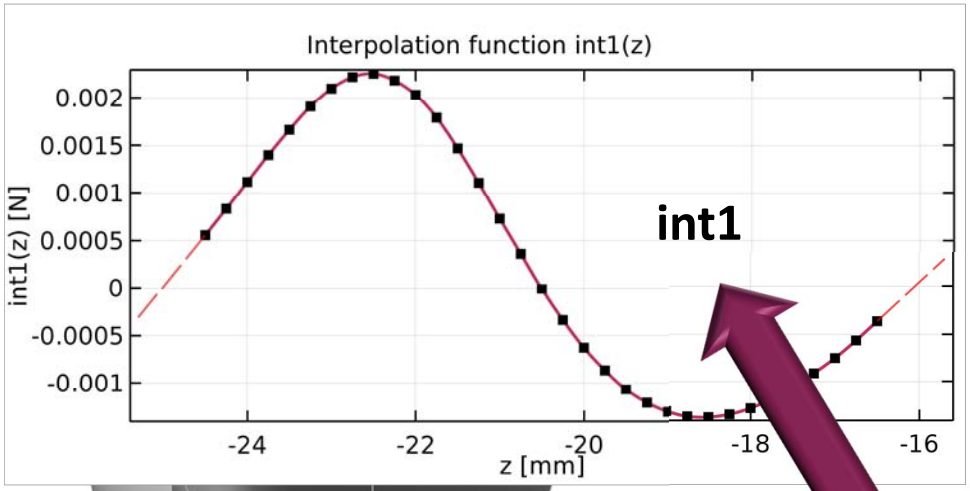
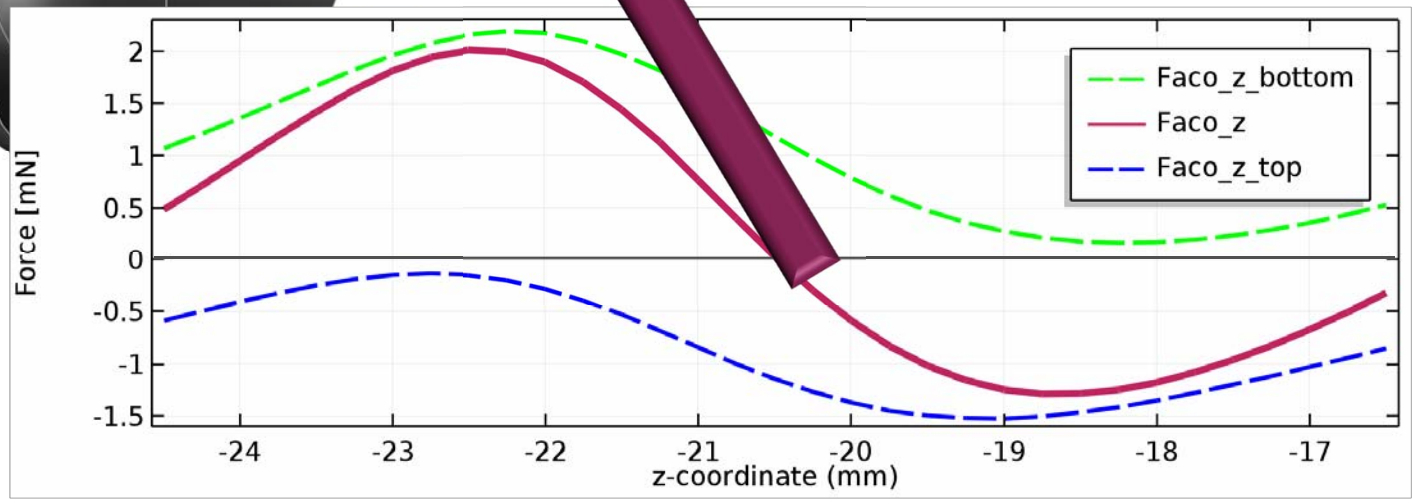


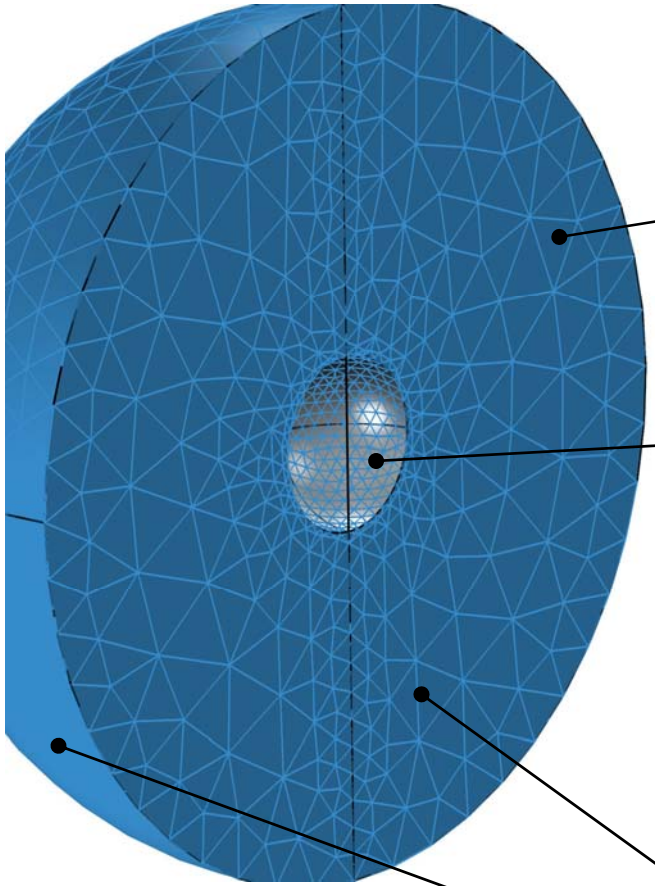
resulting force from acoustic radiation pressure

$F_{aco.z}$



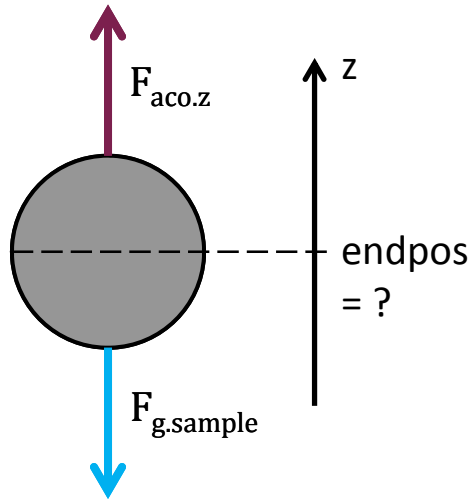
Model Development: Study 6

Sample position balance (Frequency Domain, prestressed)



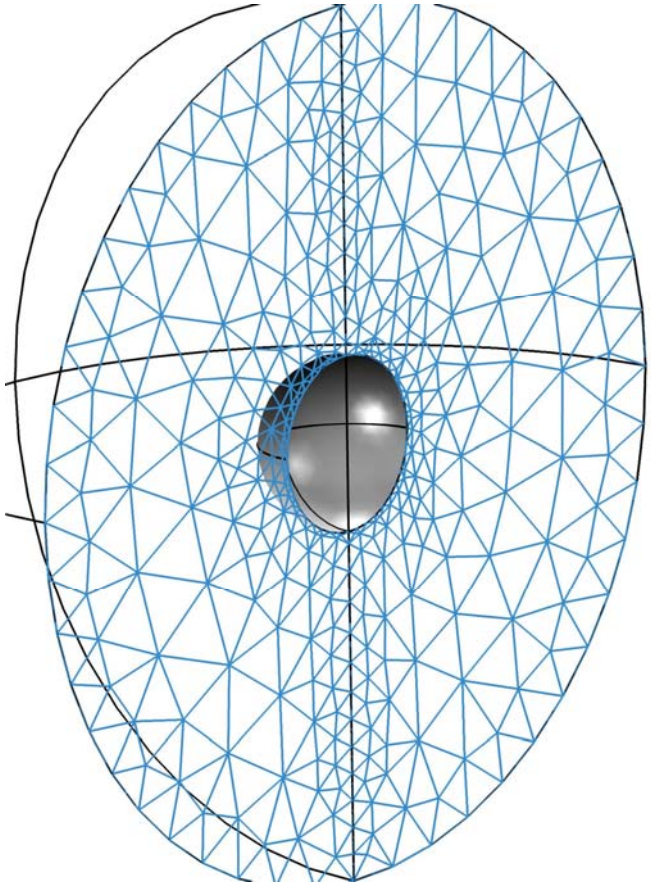
1st study step
(Stationary solution):

$F_{aco.z} = F_{g.sample}$
(balance equation)



Model Development: Study 6

Sample position balance (Frequency Domain, prestressed)



Example:
with
$Ø_{sample}$ = 4 mm
ρ_{sample} = 4 g/cm³

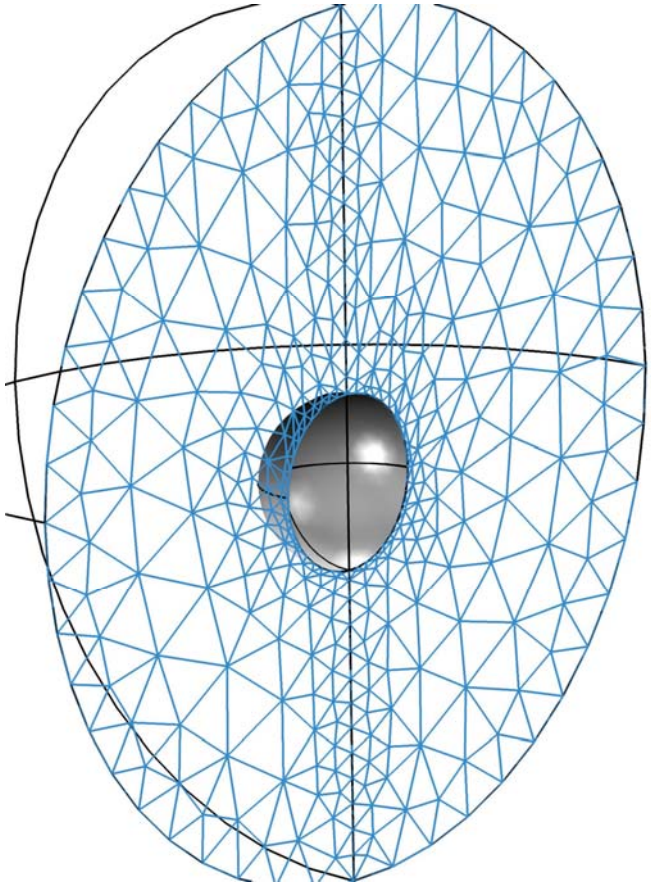
→ endpos = -21.38 mm

Mathematics: Global ODEs and DAEs (ge)

$$\boldsymbol{int1(endpos) - Fg\_sample = 0}$$

Model Development: Study 6

Sample position balance (Frequency Domain, prestressed)



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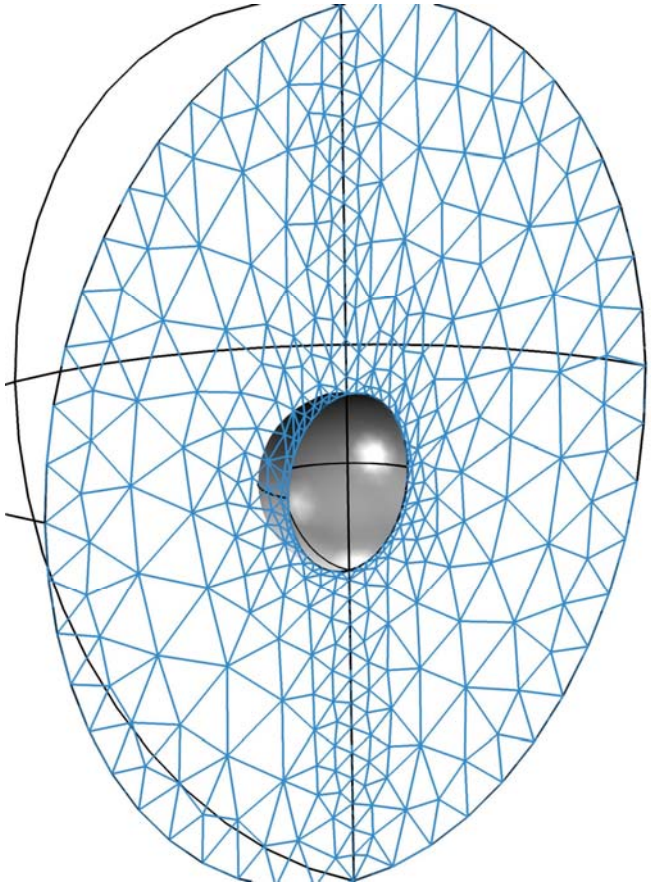
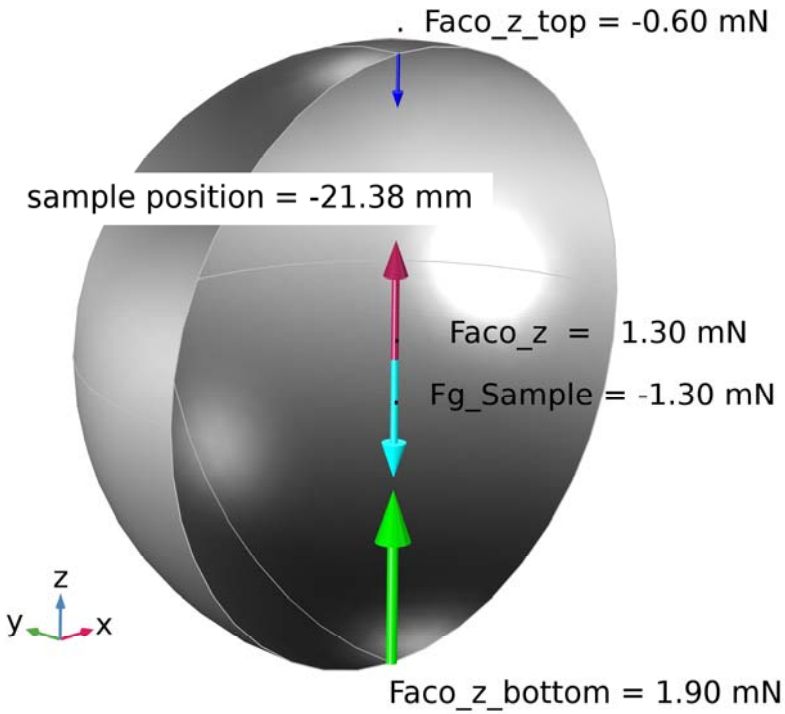
Model Development: Study 6

Sample position balance (Frequency Domain, prestressed)

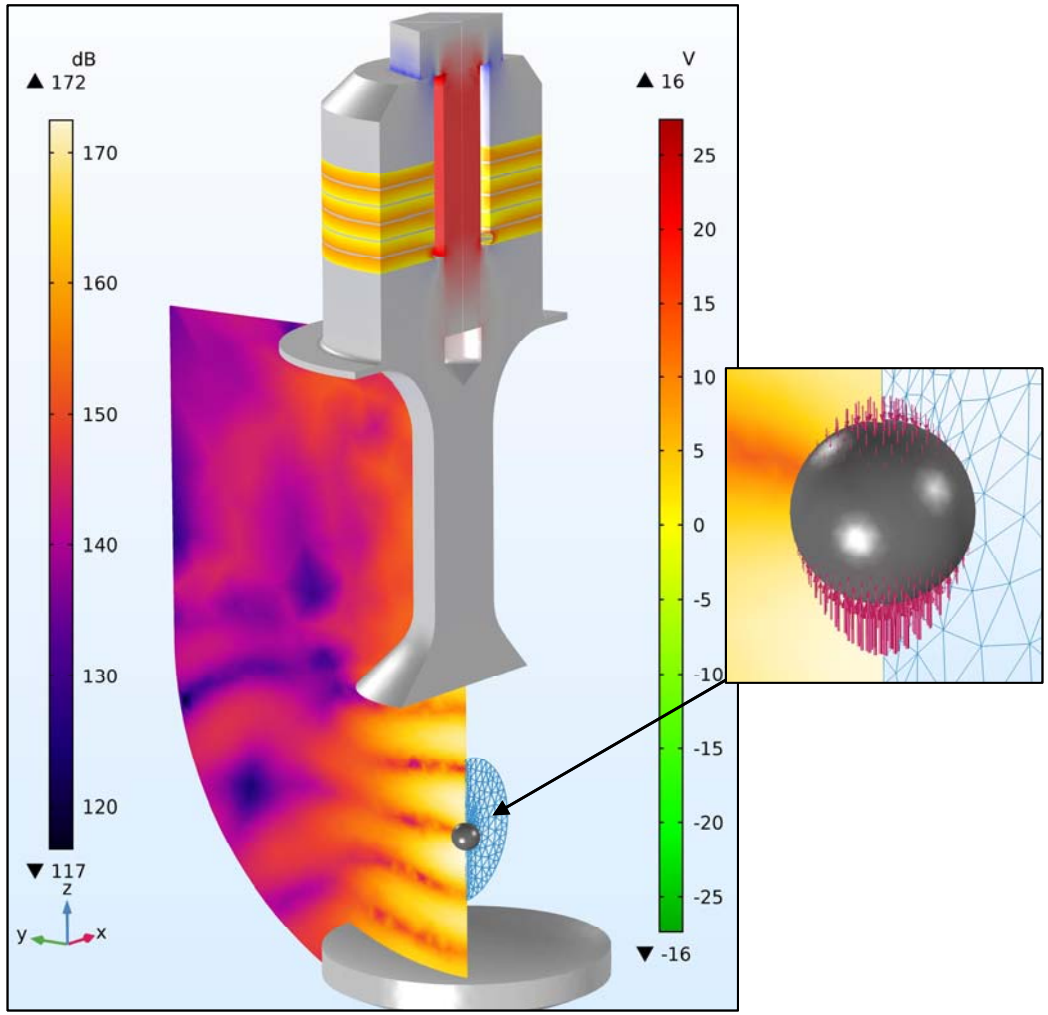


2nd study step (Frequency Domain):



Model: The Present State

Acoustic Upside-down Levitator with a Solid Sample (Study 1 - 6)



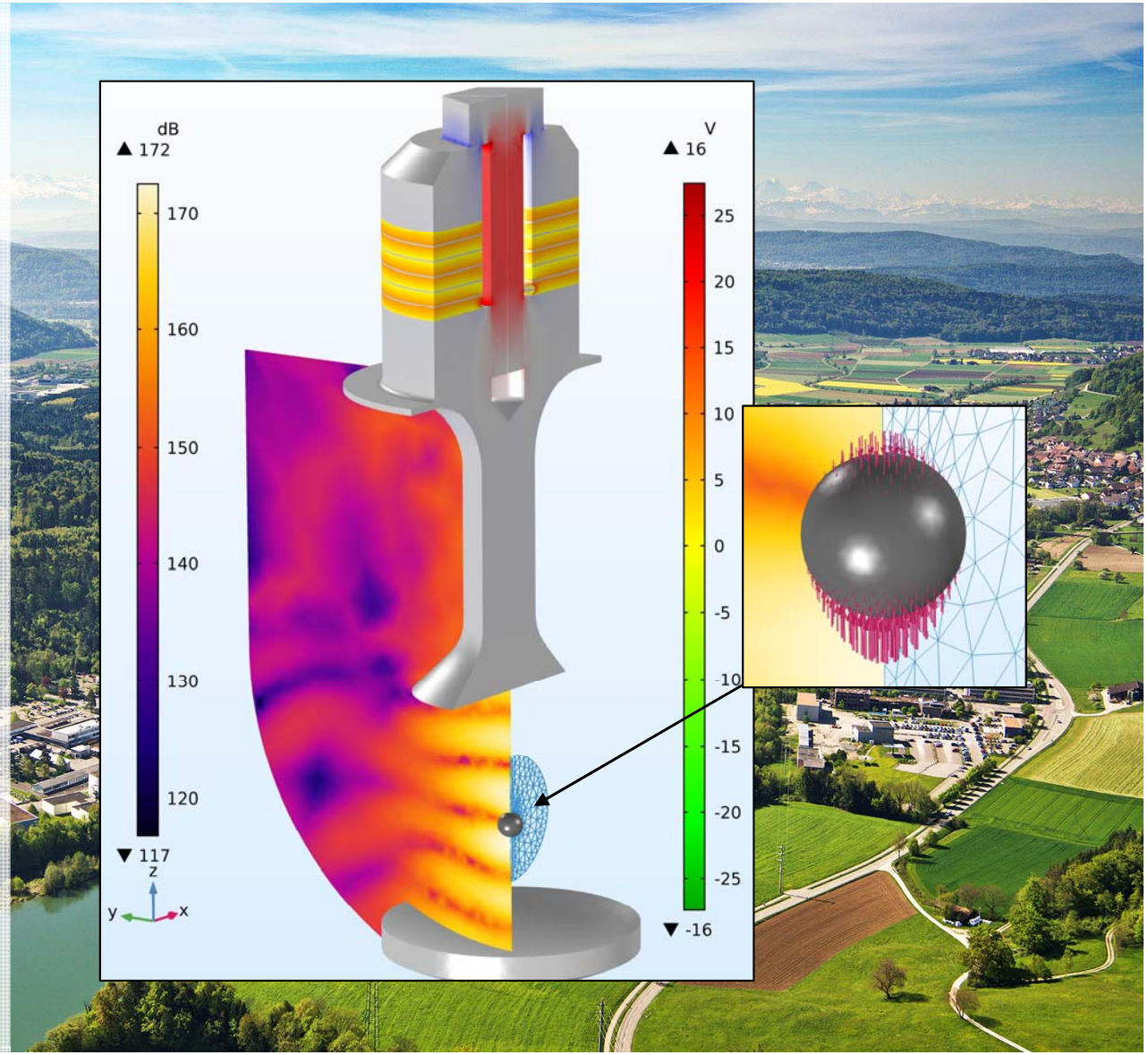
What is still missing (further tasks):

- radial forces on the sample
- acoustic streaming (gas convection)
- dynamic sample motions

Next time!

Acoustic Upside-down Levitator with a Solid Sample:

Set up with COMSOL Multiphysics®

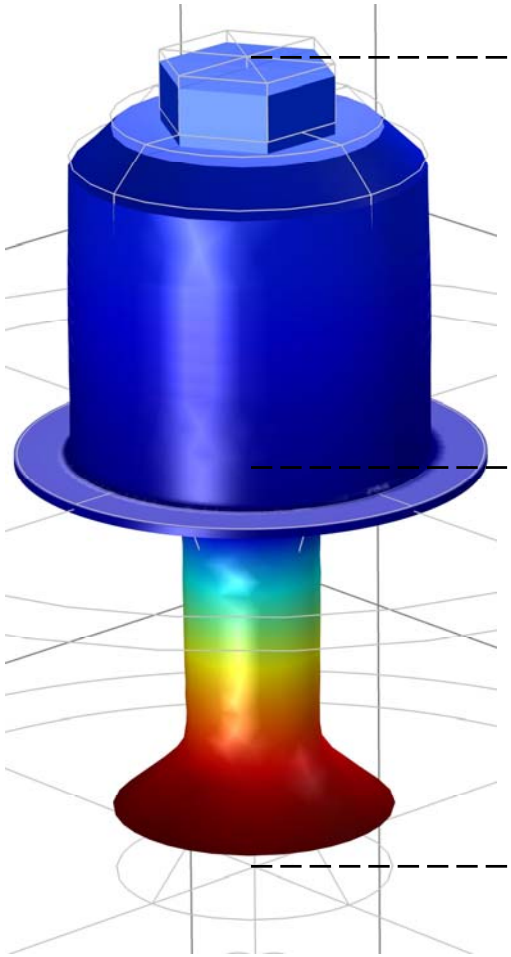


My thanks go to

- Ernst Günter Lierke
- Mads Herring Jensen

Appendix: Model Development: Study 2

Transducer geometry (Eigenfrequency, prestressed)



small axial amplitude
(velocity antinode)

axial unmoved
(velocity node)

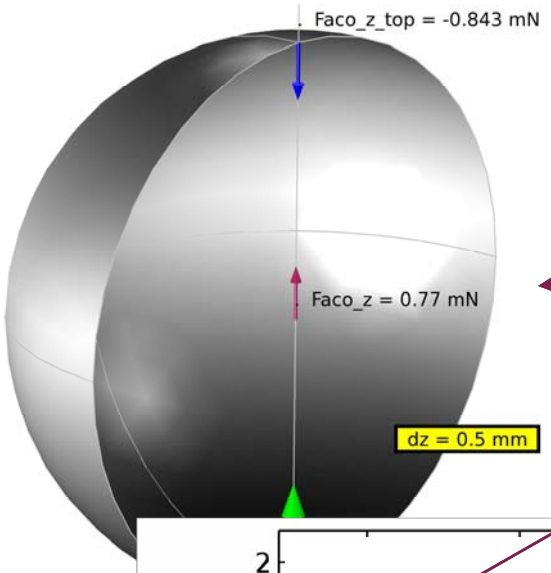
larger axial amplitude
(velocity antinode)

$$length \sim \frac{1}{frequency}$$

Possible scaling of the levitator (transducer, sample and levitation field) by means of **frequency**

Appendix: Model Development: Study 5

Acoustic levitation force progression (Frequency Domain, prestressed)



resulting force from acoustic radiation pressure

$$F_{aco.z} = F_{aco.z.bottom} + F_{aco.z.top}$$

pressure node of the sound field