Acoustic Levitation

Levitation of single solid or liquid samples

in

ultrasonic single-axis standing-wave levitators

Dipl.-Ing. Lothar Holitzner, 10.10.2007

Content

1. Overview

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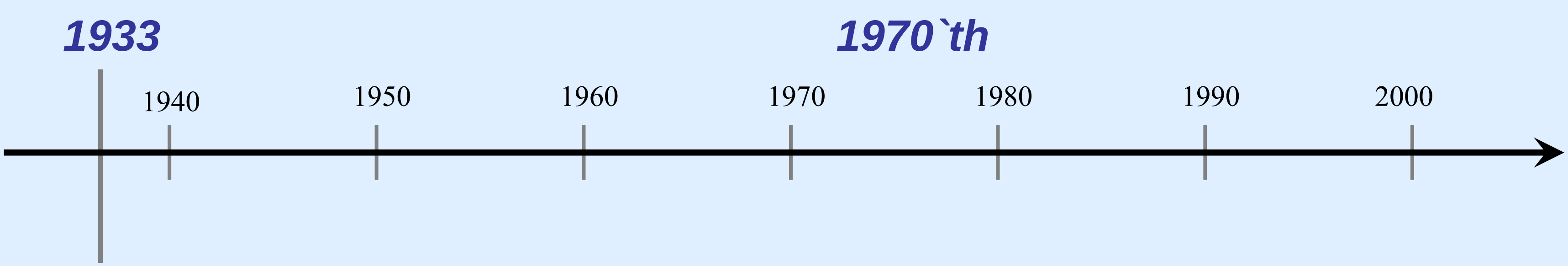
1.1 History

Fields of Application



K. Bücks, H. Müller,
Z. Phys. 84 (1933) 75.

NASA / ESA
Space applications
micro gravitation
„containerless processing“
material, phys, biolog. exp.

Terrestrial appl.
meteorologic,
chemical,
medical, ...

1.2 Features

<u>design :</u>	- compact table instrument	
<u>sample</u>		
- material :	- conductive / non conductive	
	- magnetizable / non magnetizable	
- aggregate state :	- solid / liquid / gaseous	here : solid or liquid
- position :	- stable	
<u>carrier fluid :</u>	- gas / liquid	here : gas

2. Basics

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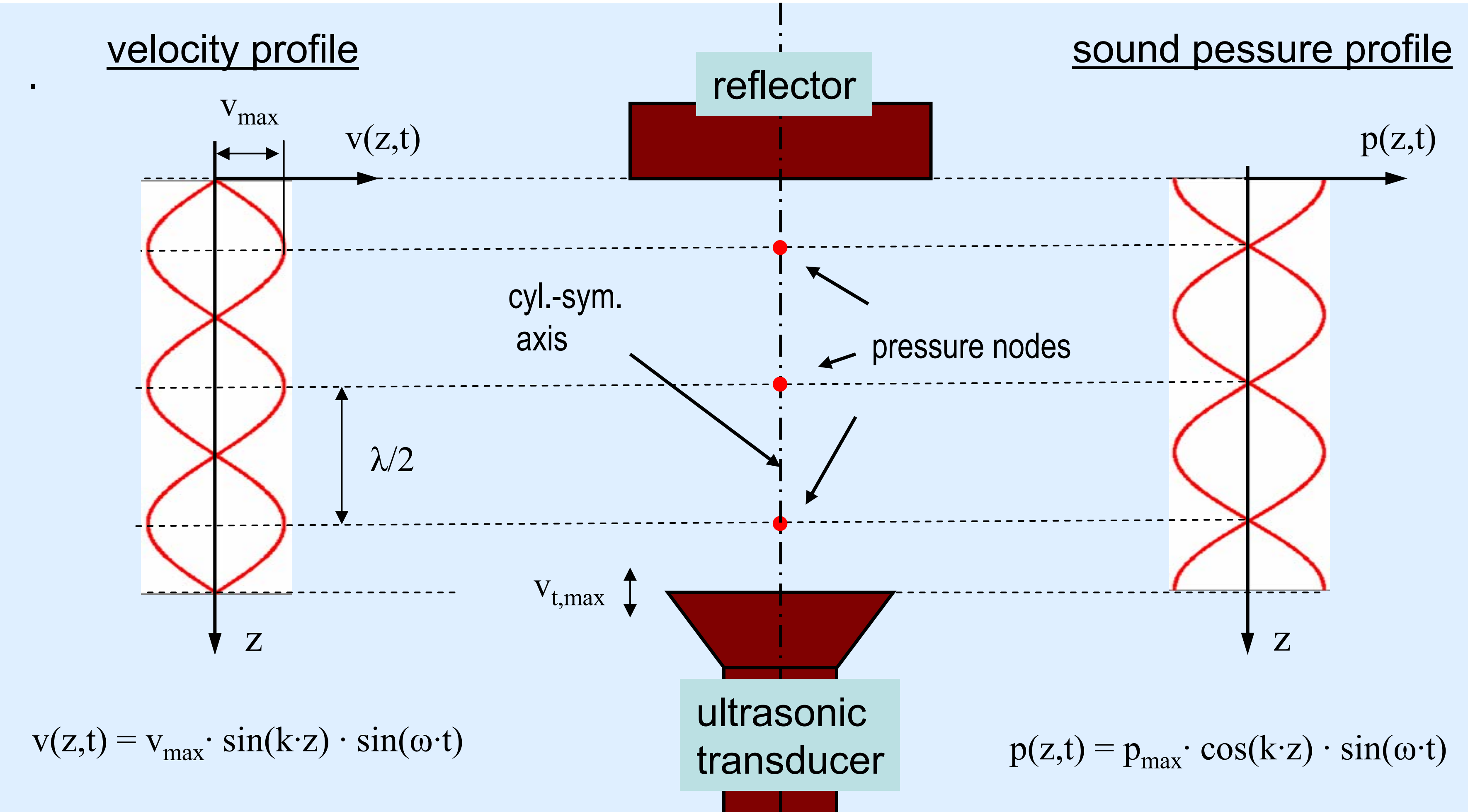
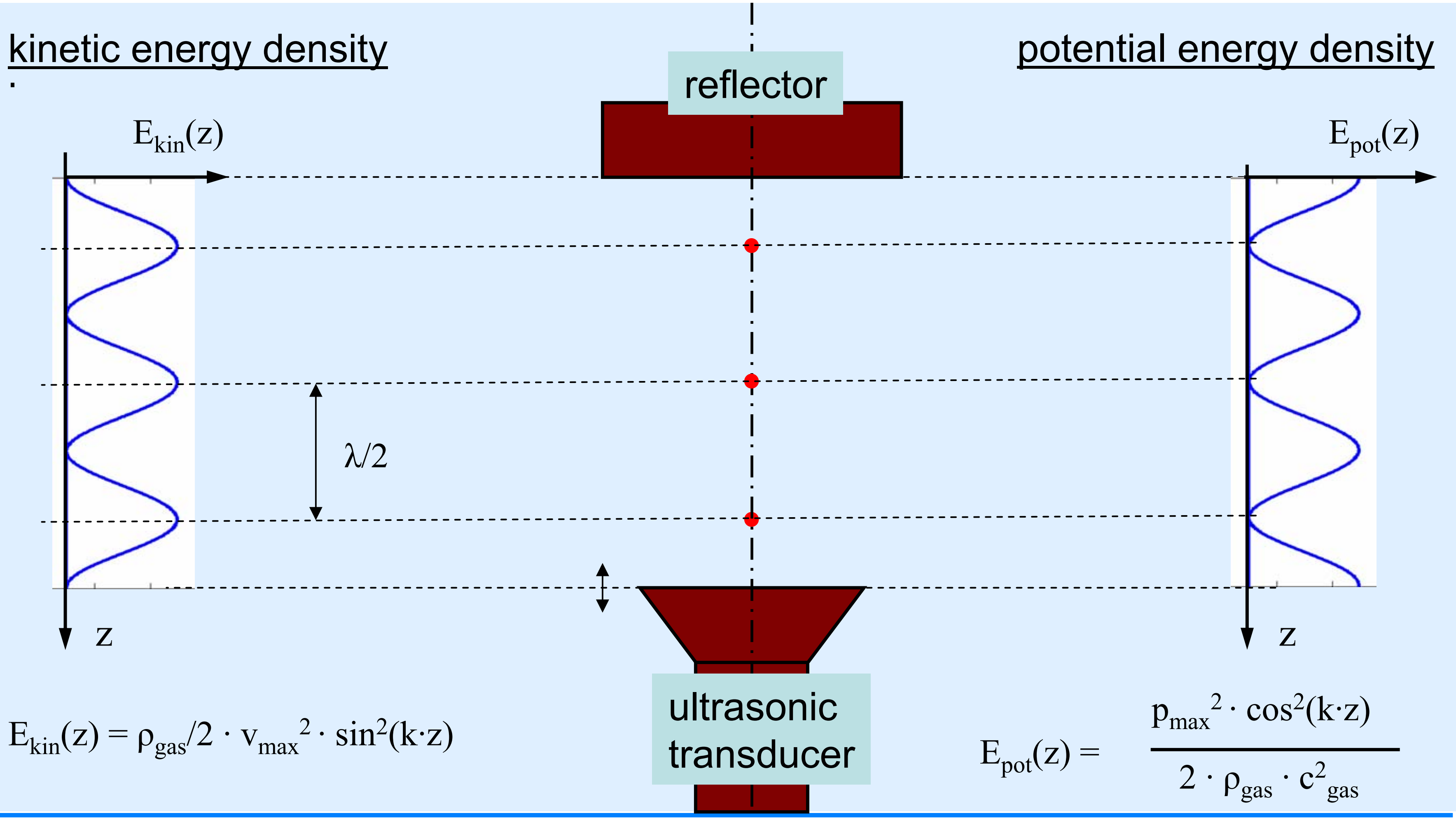
2.1 Principle : Ultrasonic standing wave



2.1 Principle : Energy density in the soundfield



$$E_{kin}(z) = \rho_{gas}/2 \cdot v_{max}^2 \cdot \sin^2(k \cdot z)$$

$$E_{pot}(z) = \frac{p_{max}^2 \cdot \cos^2(k \cdot z)}{2 \cdot \rho_{gas} \cdot c^2_{gas}}$$

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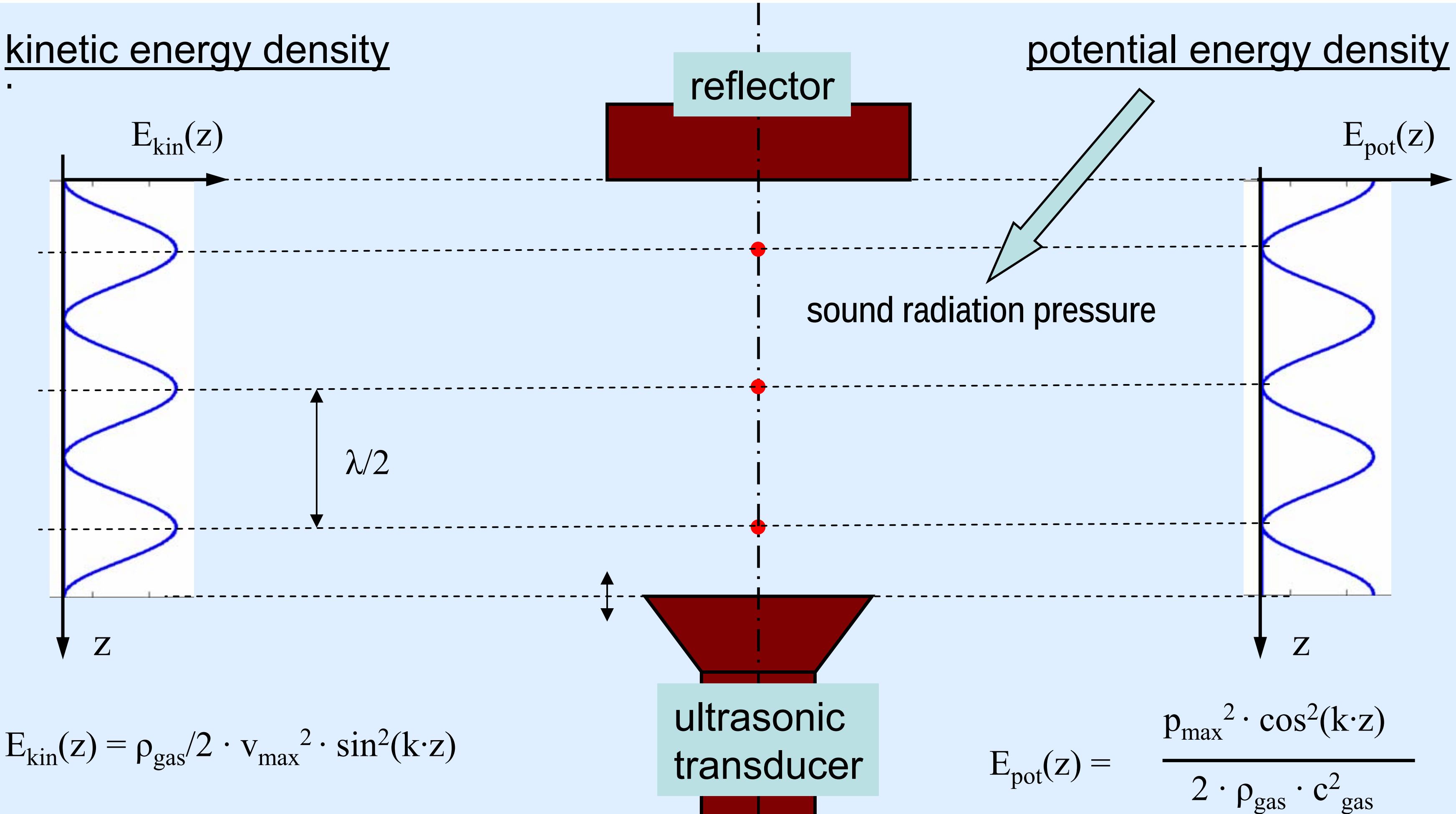

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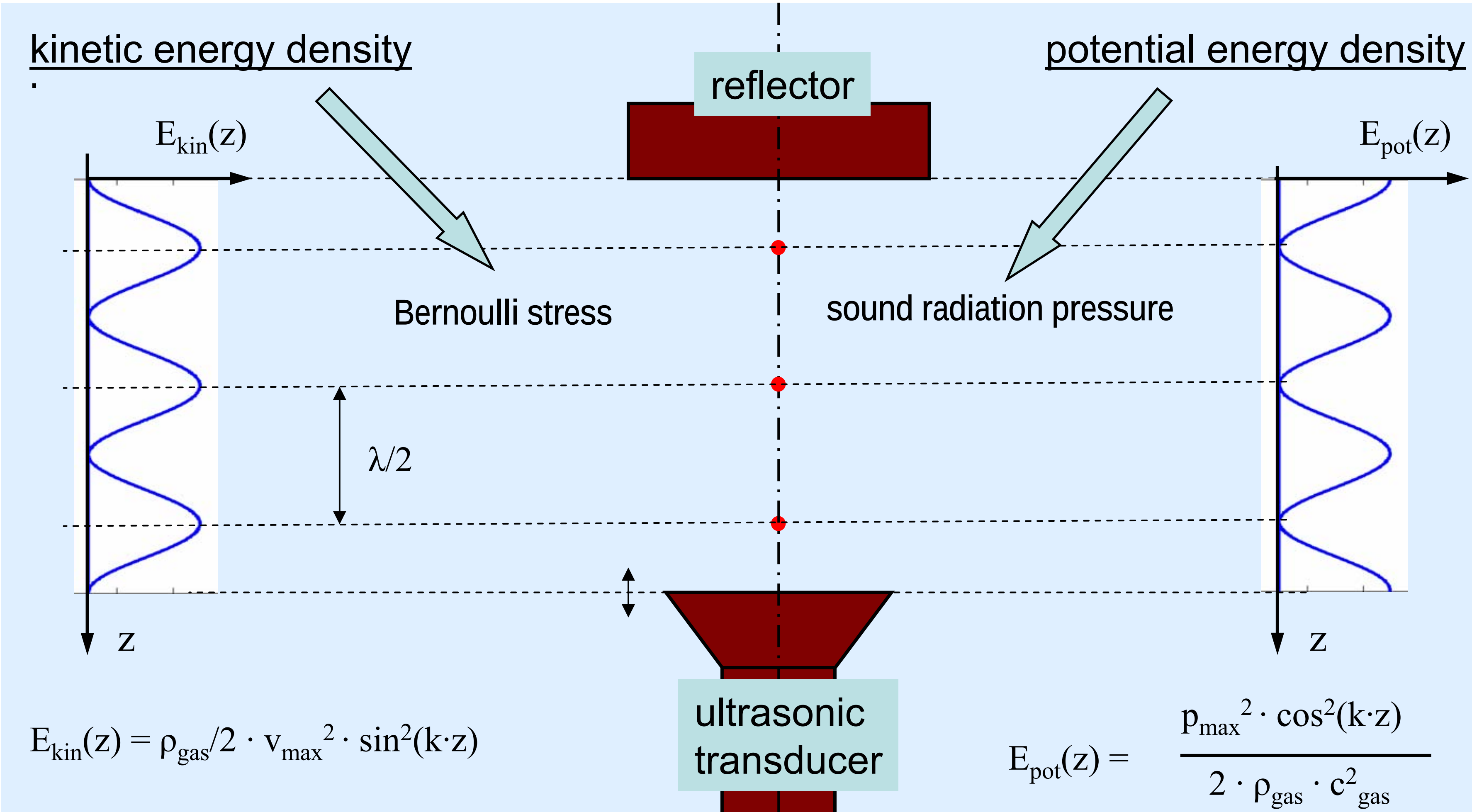

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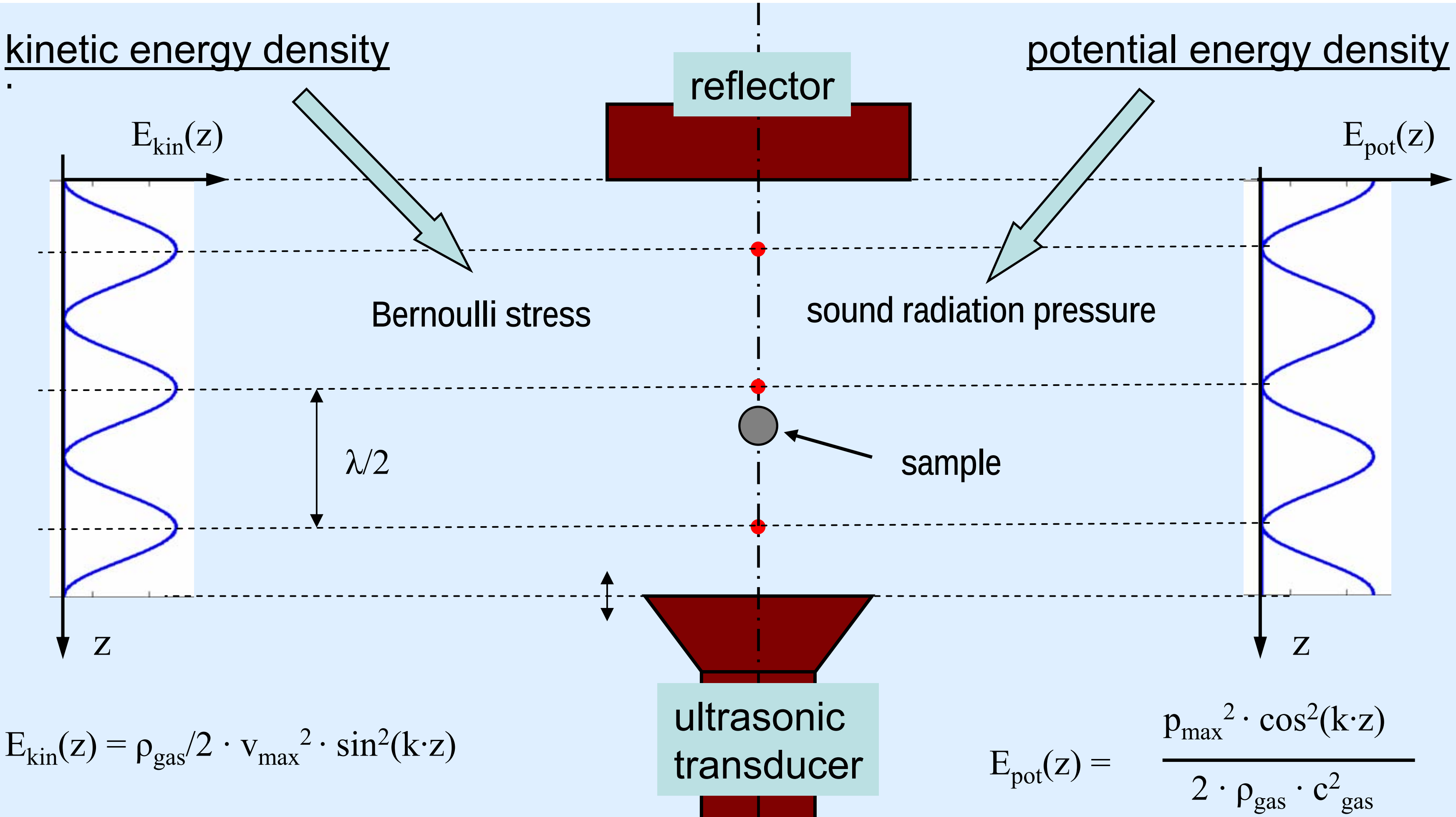

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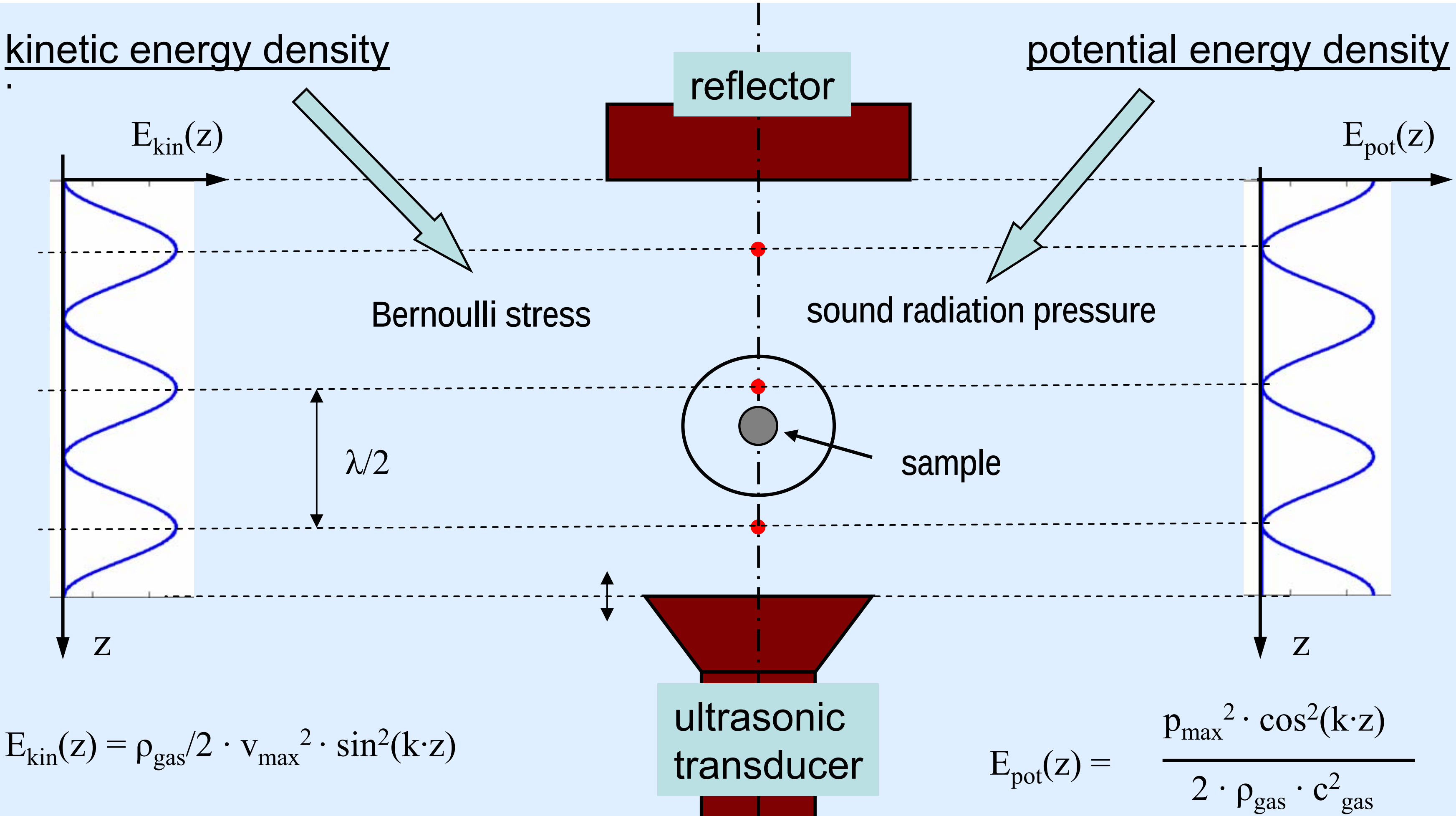

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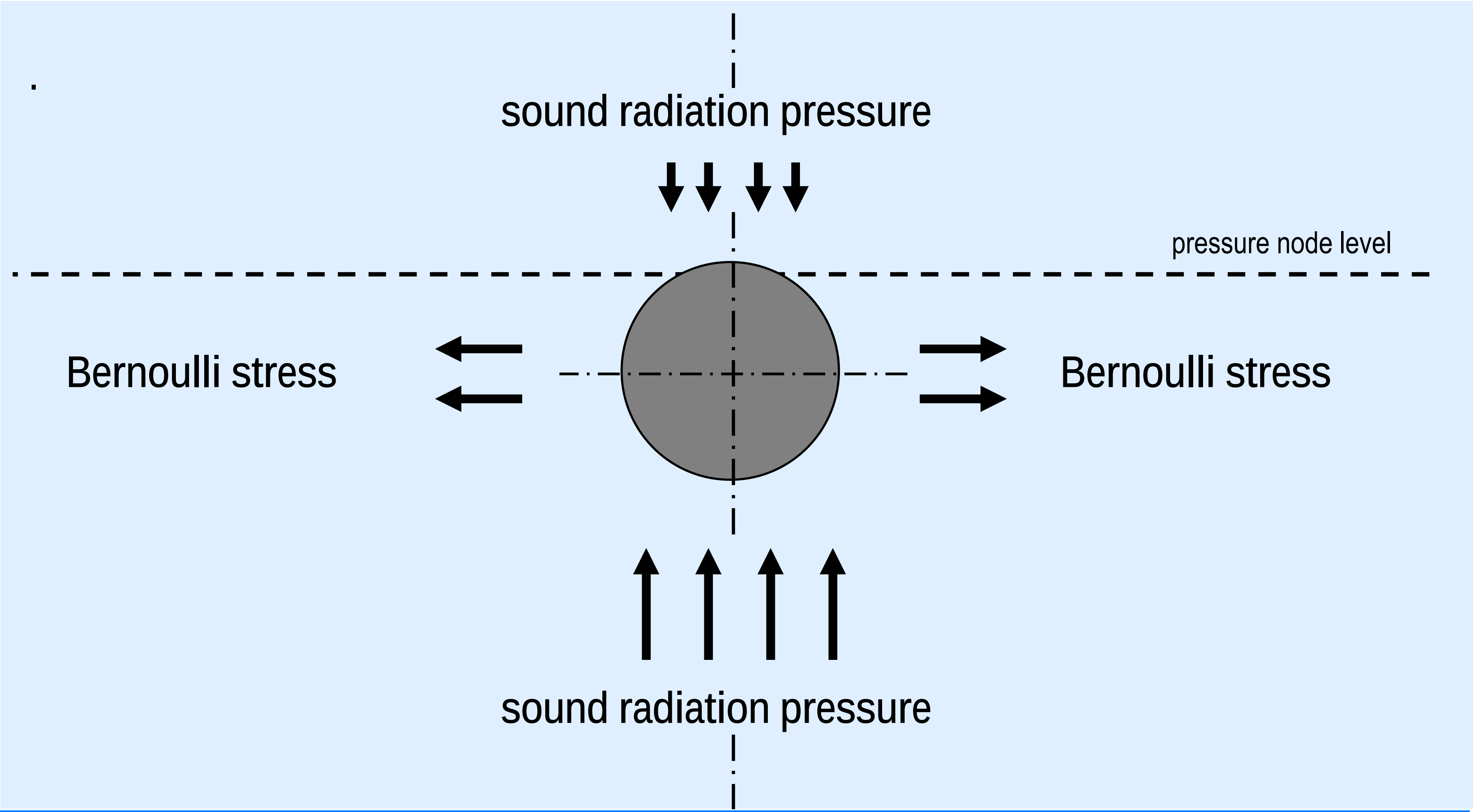
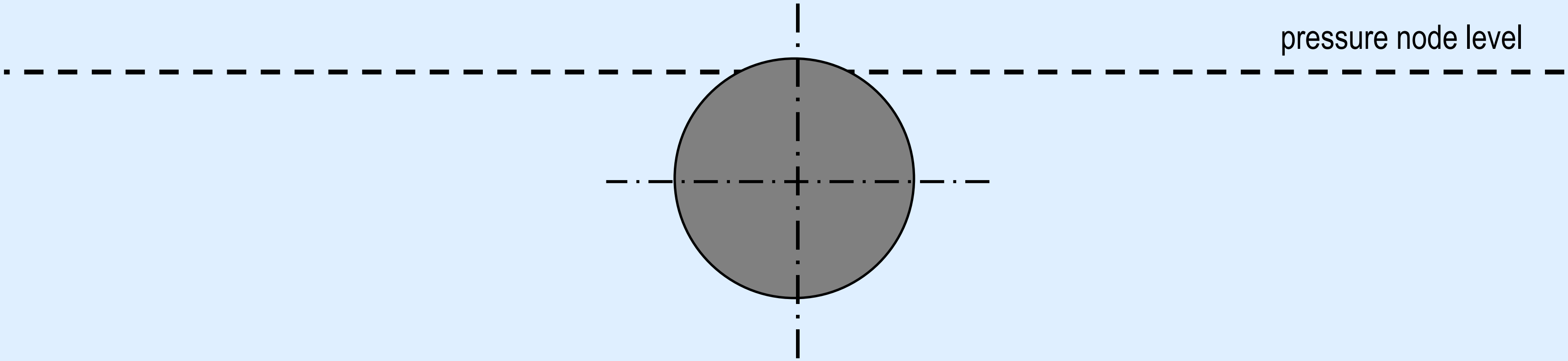
2.1 Principle : Stable position near the pressure node



2.1 Principle : Axial acoustic levitation force



$$F_{ac,axial} = \frac{5}{64\cdot\pi}\cdot\rho_{gas}\cdot c_{gas}^{2}\cdot\left(\frac{v_{max}}{f}\right)^{2}\cdot f_{d}\left(\frac{d_{s}}{\lambda}\right)\cdot\sin\left(4\cdot\pi\cdot\frac{\Delta Z}{\lambda}\right)$$

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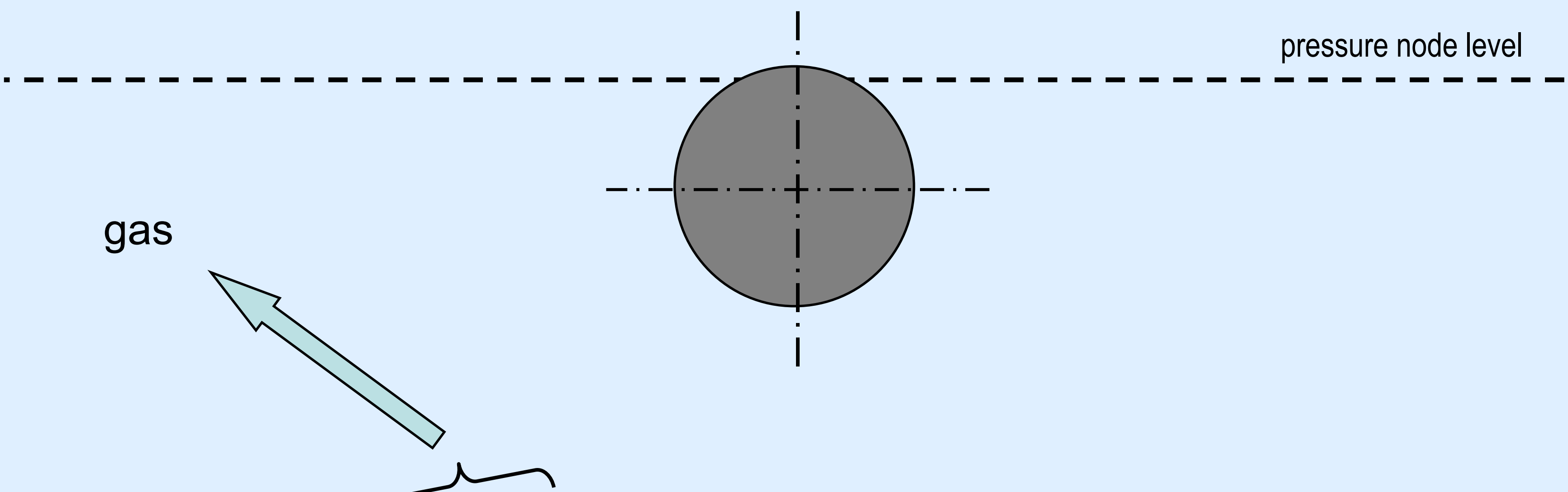

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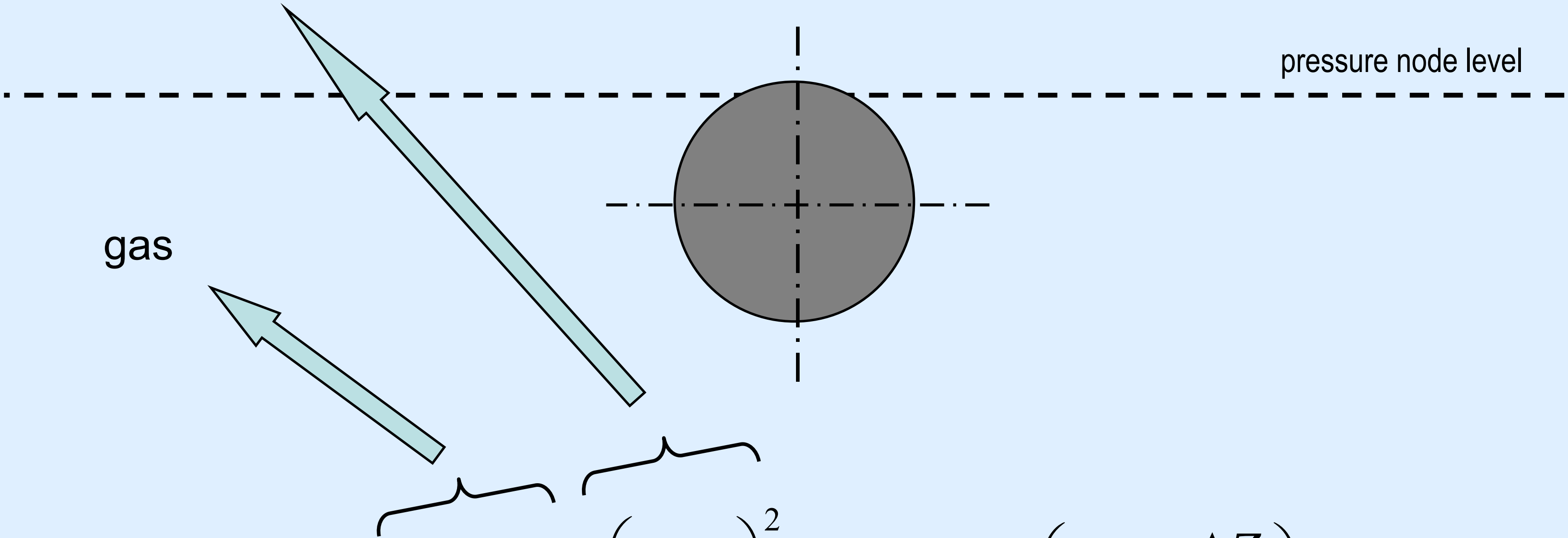

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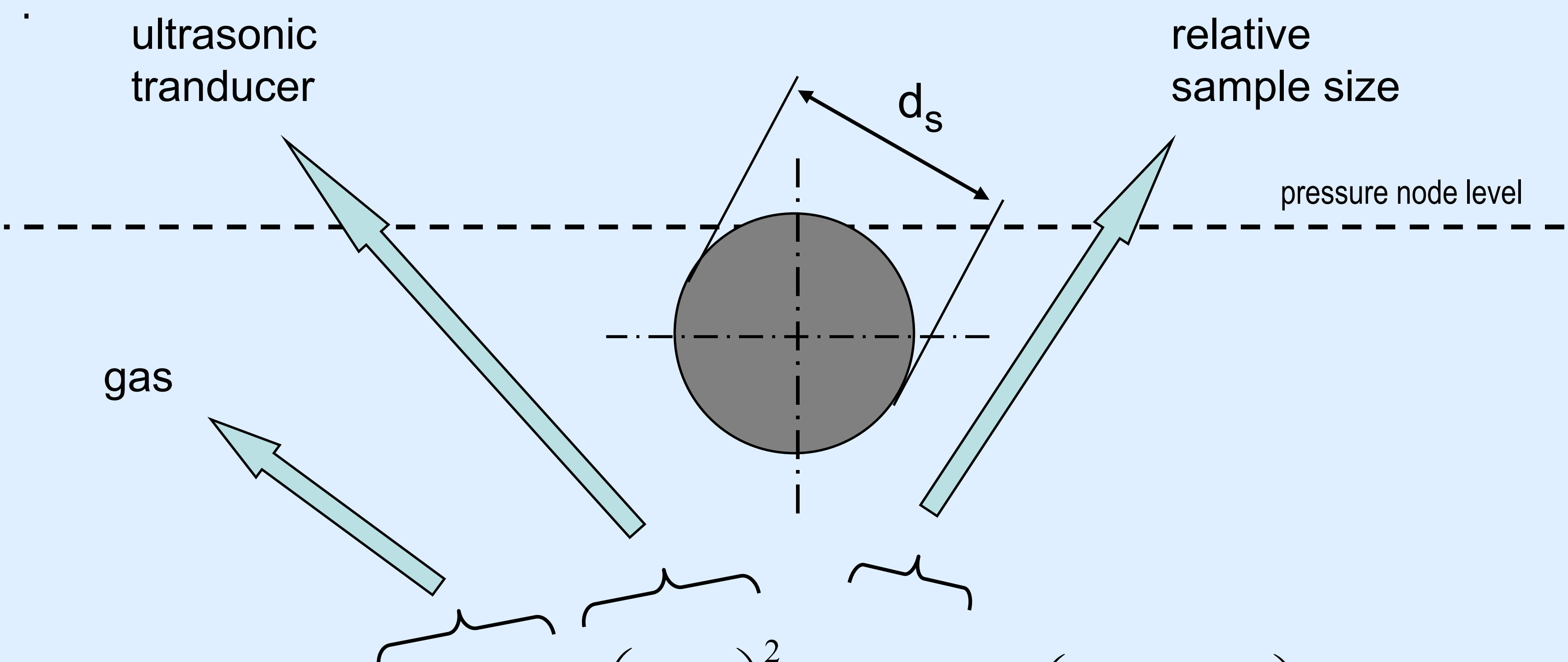

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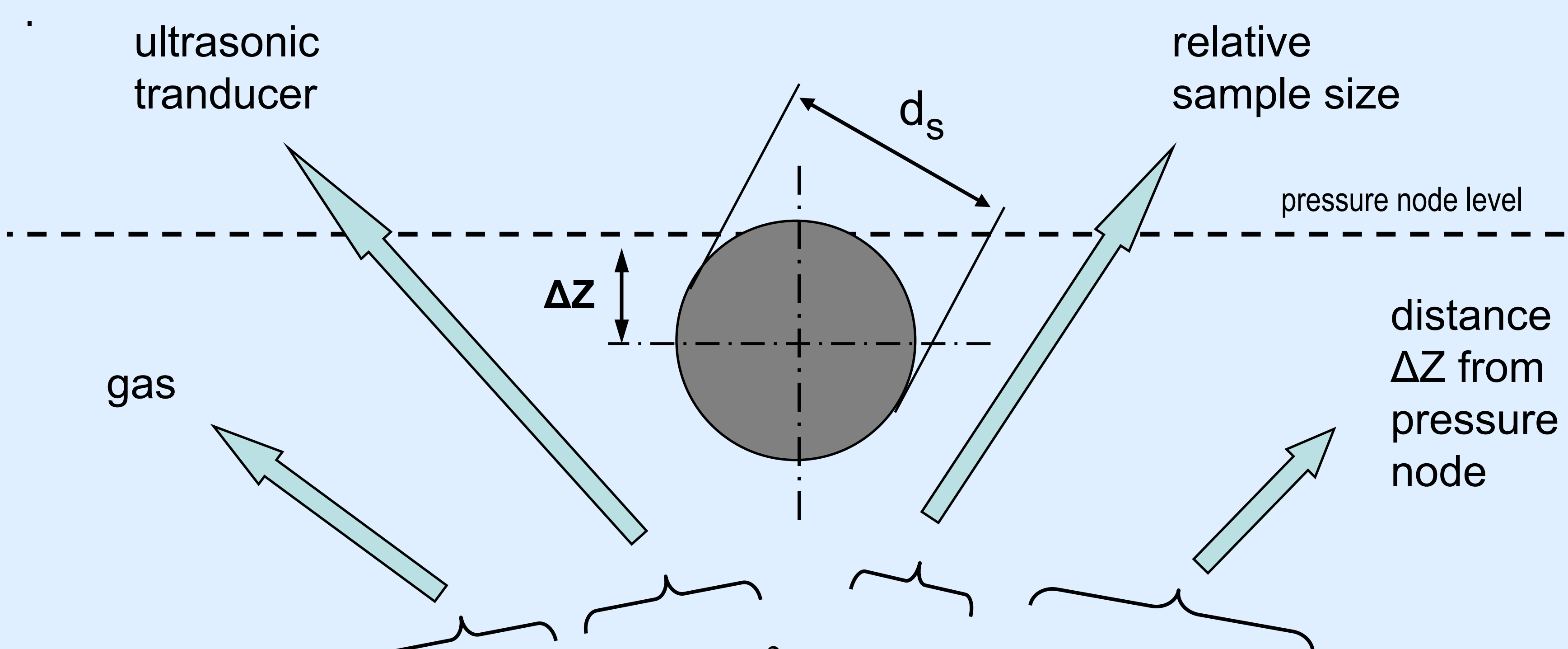

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2.2 Typical effects : Acoustic streaming

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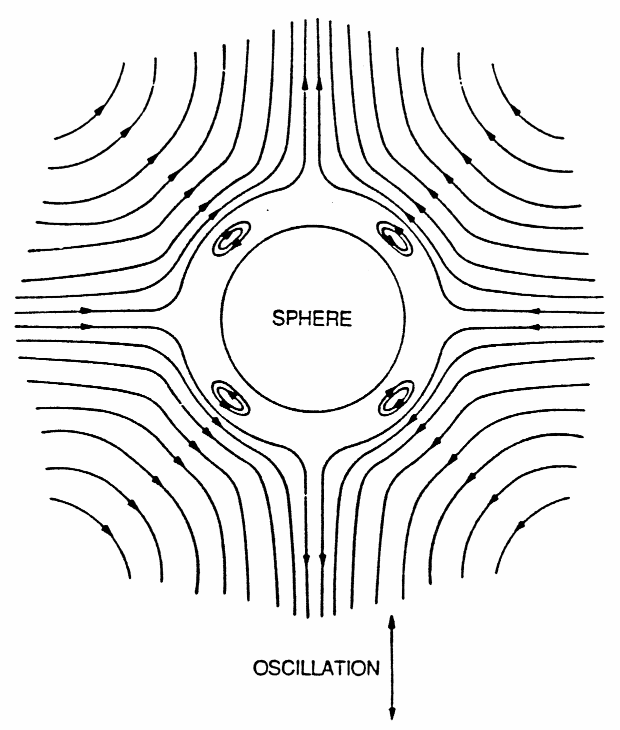
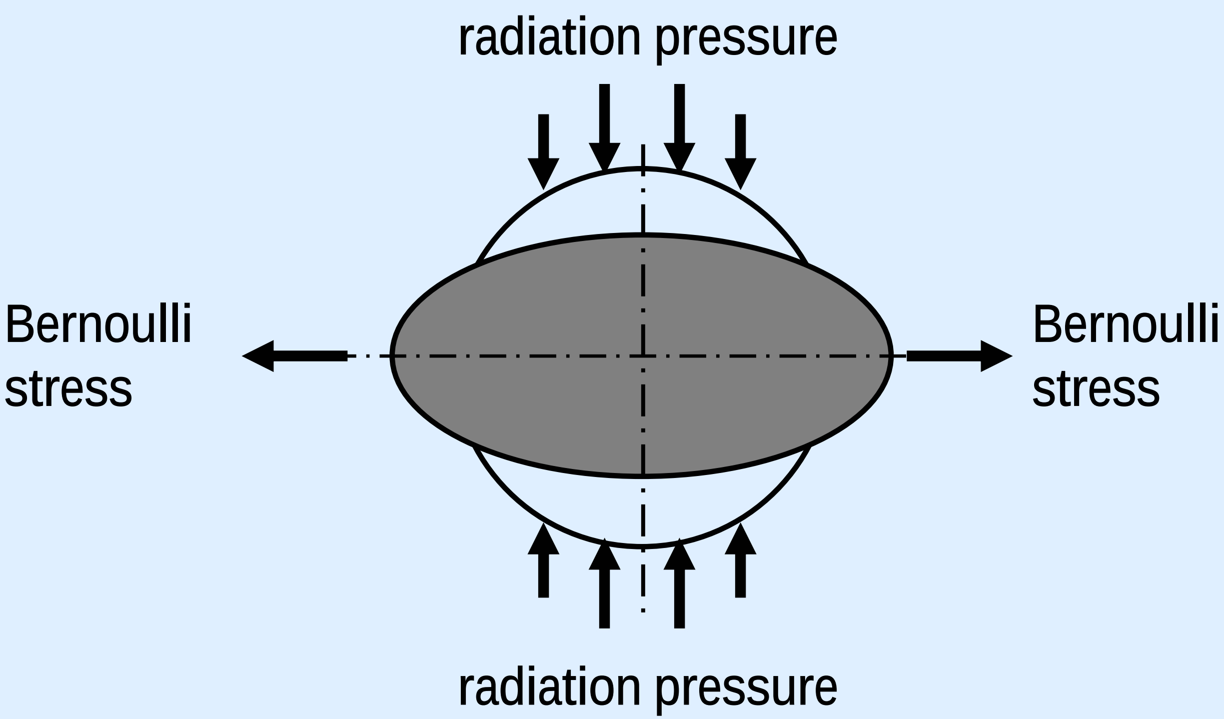


Side view of the acoustically induced convection near a levitated sphere /1/

/1/ Lee,C.P., Wang, T.G., Outer acoustic streaming, J. Acoust. Soc. Am., 88(5): 2367-2375, 1990

2.2 Typical effects : Deformation of liquid samples



Deformation of a ac. levitated 35µl water drop /2/

/2/ Holitzner, L., Verbesserung der Funktions-Charakteristik eines elektrostatisch akustischen Hybridlevitators, Diplomarbeit, FH Wiesbaden, Battelle Institut, Frankfurt/M., 1992

2.2 Typical effects : Heating

.

Examples :

d_s = 6 mm in air @ 20 kHz	water drop (20 °C)	liquid tin (300 °C)	liquid tin (700 °C)
min. sound intensity	2.5 W/cm^2	25.5 W/cm^2	37.2 W/cm^2

2.3 Limiting conditions for : solid samples

a) Sample distance from pressure node

$$F_{ac,axial} \sim \sin\left(4 \cdot \pi \cdot \frac{\Delta Z}{\lambda}\right)$$

$$\sin\left(4 \cdot \pi \cdot \frac{\Delta Z}{\lambda}\right) \leq 1$$

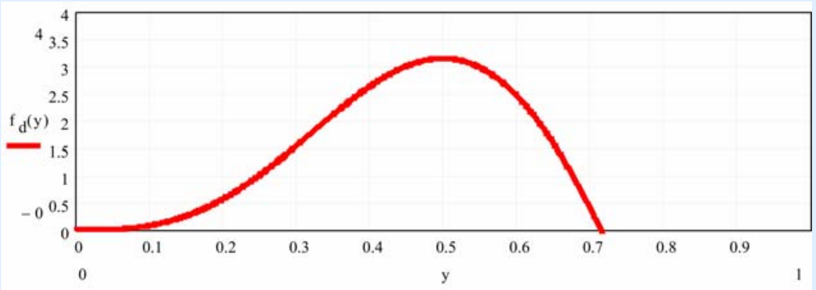
$$\Delta Z \leq \frac{1}{8}\lambda$$

safety factor $\Phi_S = \dfrac{1}{\sin(4 \cdot \pi \cdot \frac{\Delta Z}{\lambda})} \geq 1$

b) Sample size

$$F_{ac,axial} \sim f_d\left(\frac{d_s}{\lambda}\right)$$

$$f_d\left(\frac{d_s}{\lambda}\right) = \sin\left(2\pi \frac{d_s}{\lambda}\right) - 2\pi \frac{d_s}{\lambda} \cdot \cos\left(2\pi \frac{d_s}{\lambda}\right)$$



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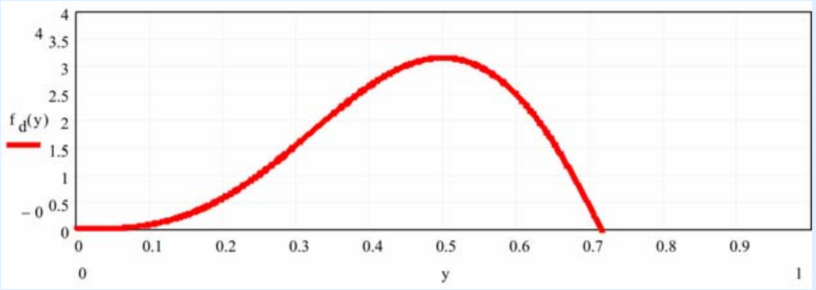

⇨ $d_s \leq \frac{1}{2}\lambda = \frac{1}{2} \cdot \frac{c_{gas}}{f}$

2.3 Limiting conditions for : solid samples

b) Sample size

Examples :

	$d_{s,max}$ @ 20 °C	$d_{s,max}$ @ 400 °C
20 kHz in air	8.5 mm	13.0 mm
30 kHz in air	5.7 mm	8.6 mm
60 kHz in air	2.8 mm	4.3 mm
20 kHz in Ar	7.9 mm	
30 kHz in Ar	5.2 mm	

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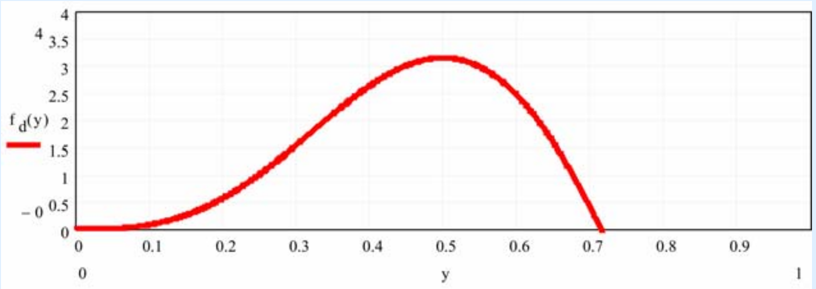

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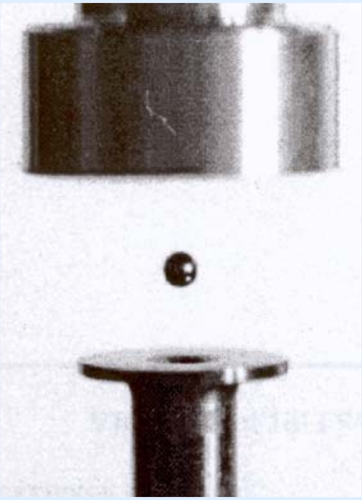

2 mm steel sphere positioned in a 58 kHz levitator /3/

/3/ Schnitzler,A., Aufbau einer akustischen Falle, Joh. Gutenb.-Uni.Mainz, 1998

2.3 Limiting conditions for : liquid samples

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$$\Delta Z \leq \frac{1}{8}\lambda$$

→ safety factor $\Phi_S = \frac{1}{\sin(4 \cdot \pi \cdot \frac{\Delta Z}{\lambda})} \geq 1$

b) Sample size

$$d_s \leq \frac{1}{2}\lambda$$

$$Bo = \frac{P_{hydrostatic}}{P_{capillary}} = \frac{g}{4} \cdot \frac{\rho_{sample}}{\sigma_{sample}} \cdot d_{sample}^2$$

$$Bo_{acoustic} \leq 1.4$$

2.3 Limiting conditions for : liquid samples

a) Sample distance from pressure node

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$$Bo_{acoustic} \leq 1.4$$

→ $$d_{s,liquid} \leq \sqrt{\frac{5.6}{g} \cdot \frac{\sigma_{sample}}{\rho_{sample}}}$$

2.3 Limiting conditions for : liquid samples

b) Sample size

Examples :

	$d_{s,liquid,max}$	$m_{s.max}$
water (20 °C)	6.4 mm	0.14 g
liquid tin (300°C)	6.6 mm	1.05 g
liquid tin (700 °C)	6.5 mm	0.98 g

.

$$d_s \leq \frac{1}{2}\lambda$$

$$Bo = \frac{P_{hydrostatic}}{P_{capillary}} = \frac{g}{4} \cdot \frac{\rho_{sample}}{\sigma_{sample}} \cdot d_{sample}^2$$

$$Bo_{acoustic} \leq 1.4$$

$$\Rightarrow \quad d_{s,liquid} \leq \sqrt{\frac{5.6}{g} \cdot \frac{\sigma_{sample}}{\rho_{sample}}}$$

2.3 Limiting conditions for : liquid samples

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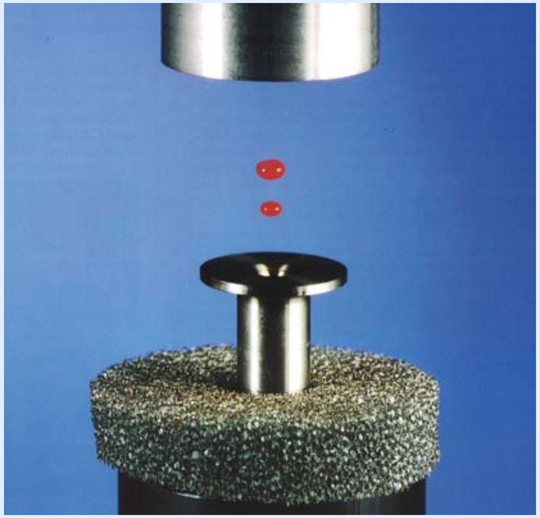


Levitated droplets in the 2nd and the 3rd pressure node of a 58 kHz levitator /4/

/4/ Lierke,E.G., Deformation and displacement of liquid drops in optimized acoustic standing wave levitators, Acta acustica, Vol.88 (2002) 206-217

2.4 Optimal conditions : Sound intensity

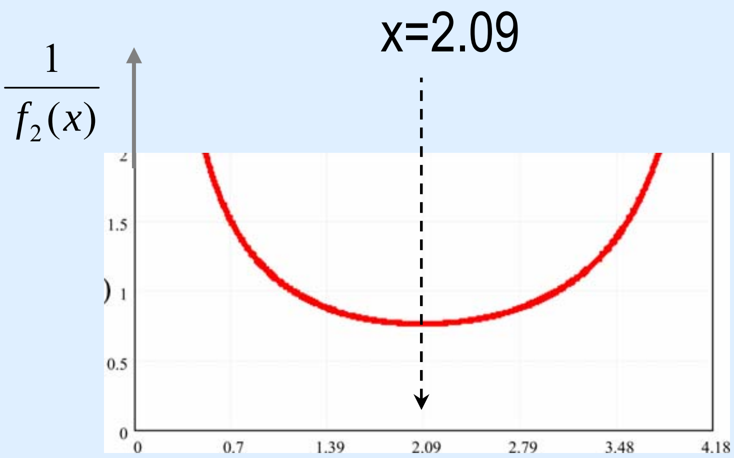
Criterion : minimal necessary sound intensity

sound intensity $$J_{sound} = \rho_{gas} \cdot c_{gas} \cdot v_{\max}^2$$

min. sound intensity $$J_{sound,\min} = \frac{8}{5} \cdot g \cdot c_{gas} \cdot \rho_s \cdot d_s \cdot \frac{1}{f_2(x)}$$

with $$f_2(x) = \frac{3}{x}\left(\frac{\sin(x)}{x} - \cos(x)\right)$$

$$x = 2 \cdot \pi \cdot \frac{d_s}{\lambda}$$



2.4 Optimal conditions : Sound intensity

Criterion : minimal necessary sound intensity

$$\lambda_{s,opt} = 3 \cdot d_s$$

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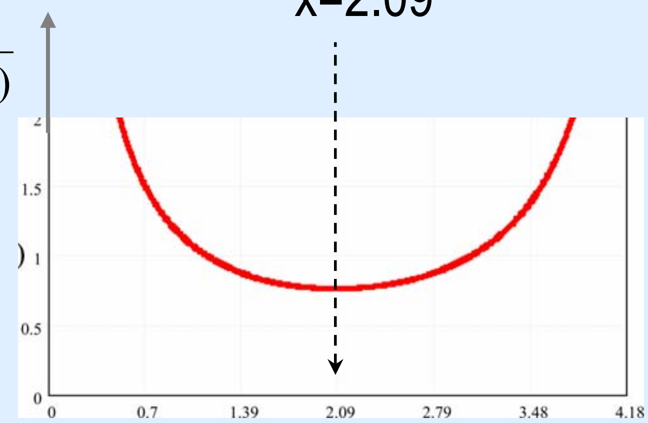
x=2.09

$$\frac{1}{f_2(x)}$$



with $$f_2(x) = \frac{3}{x}\left(\frac{\sin(x)}{x} - \cos(x)\right)$$

$$x = 2 \cdot \pi \cdot \frac{d_s}{\lambda}$$

2.4 Optimal conditions : Sample size

Criterion : minimal necessary sound intensity

$$\lambda_{opt} = 3 \cdot d_s = \frac{c_{gas}}{f_{opt}}$$

$$\Rightarrow \quad d_{s,opt} = \frac{1}{3} \cdot \frac{\sqrt{\chi_{gas} \cdot R_{gas} \cdot T_{gas}}}{f}$$

Examples : in air @	20 kHz (20 °C)	30 kHz (20 °C)	40 kHz (20 °C)	20 kHz (300 °C)	20 kHz (700 °C)
$d_{s,opt}$	5.7 mm	3.8 mm	2.9 mm	8.0 mm	10.4 mm

2.4 Optimal conditions : Sound frequency

Criterion : minimal necessary sound intensity

$$\lambda_{opt} = 3 \cdot d_s = \frac{c_{gas}}{f_{opt}}$$

$$\Rightarrow \quad f_{opt} = \frac{1}{3} \cdot \frac{\sqrt{\chi_{gas} \cdot R_{gas} \cdot T_{gas}}}{d_{s,\max}}$$

Examples : in air @	water (20 °C)	water (80 °C)	liquid tin (300 °C)	liquid tin (700 °C)
f_{opt}	17.8 kHz	19.6 kHz	24.1 kHz	31.6 kHz

3. Application and instrumentation

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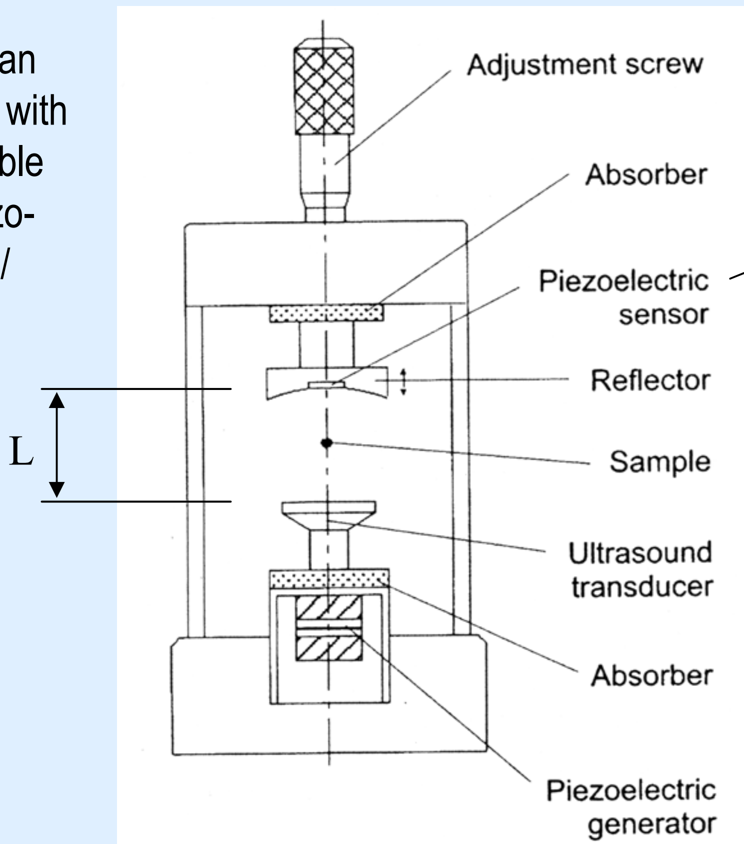
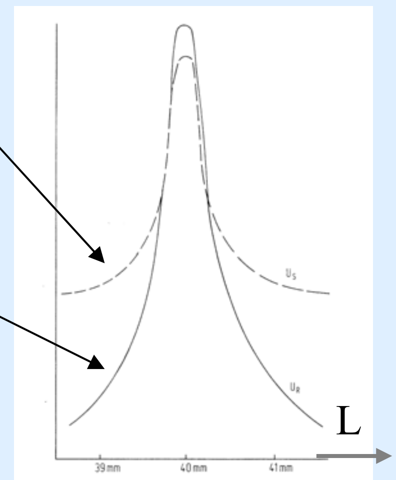
3.1 State of the art : Environment

- Typical layout of an acoustic levitator with manually adjustable reflector and piezo-electric sensor /4/



generator voltage

sensor voltage



Measured dependence between reflector sound pressure and transducer-reflector distance /5/

/4/ Lierke,E.G., Acta acustica, Vol.88 (2002) 206-217

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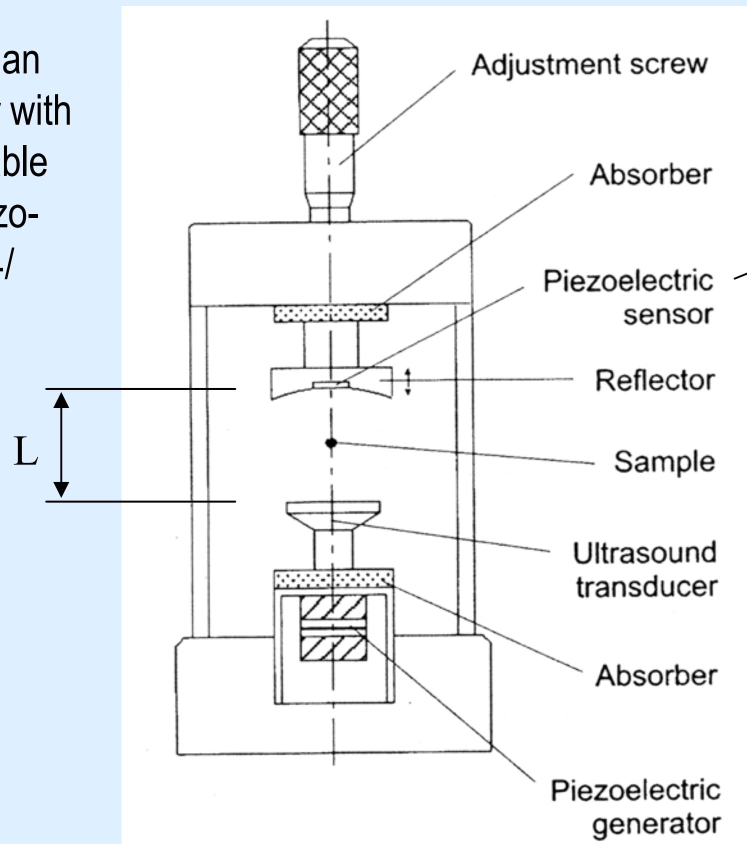

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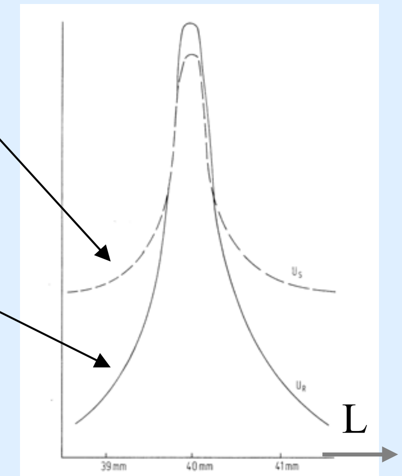

Measured dependence between reflector sound pressure and transducer-reflector distance /5/

resonance tuning

/4/ Lierke,E.G., Acta acustica, Vol.88 (2002) 206-217

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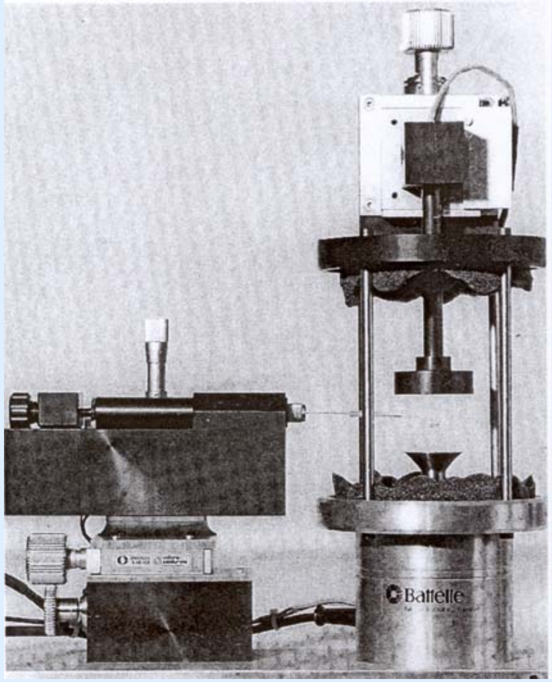
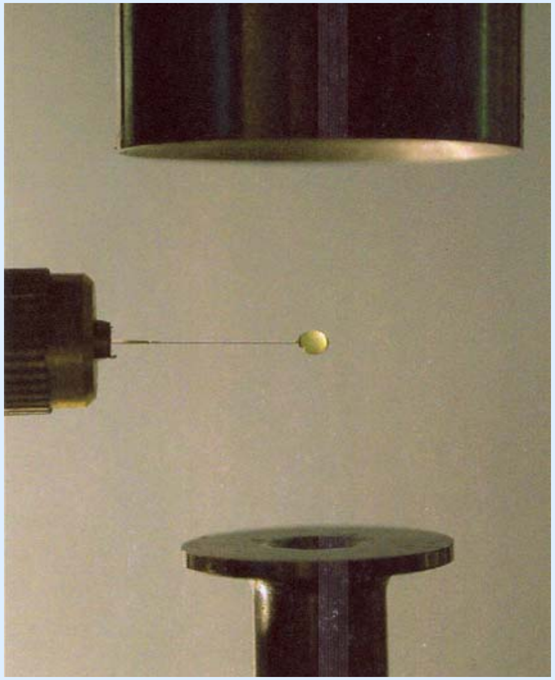


20kHz levitator with droplet injector and automatic resonance tuning /5/



Droplet implementation into a 58kHz levitator by drain tube /6/

/5/ Lierke, E.G., Akustische Positionierung – Ein umfassender Überblick über Grundlagen und Anwendunge, Acustica – acta acustica, Vol. 82 (1996) 220-237

/6/ Sprynchak, V., Ramanspektroskopische Unters. a. homog. u. inhomog. sphärischen u. sphäroiden Partikeln, Dissertation, Fak. f. Maschinenbau d. Ruhr-Universität Bochum, 2003

3.1 State of the art : Environment

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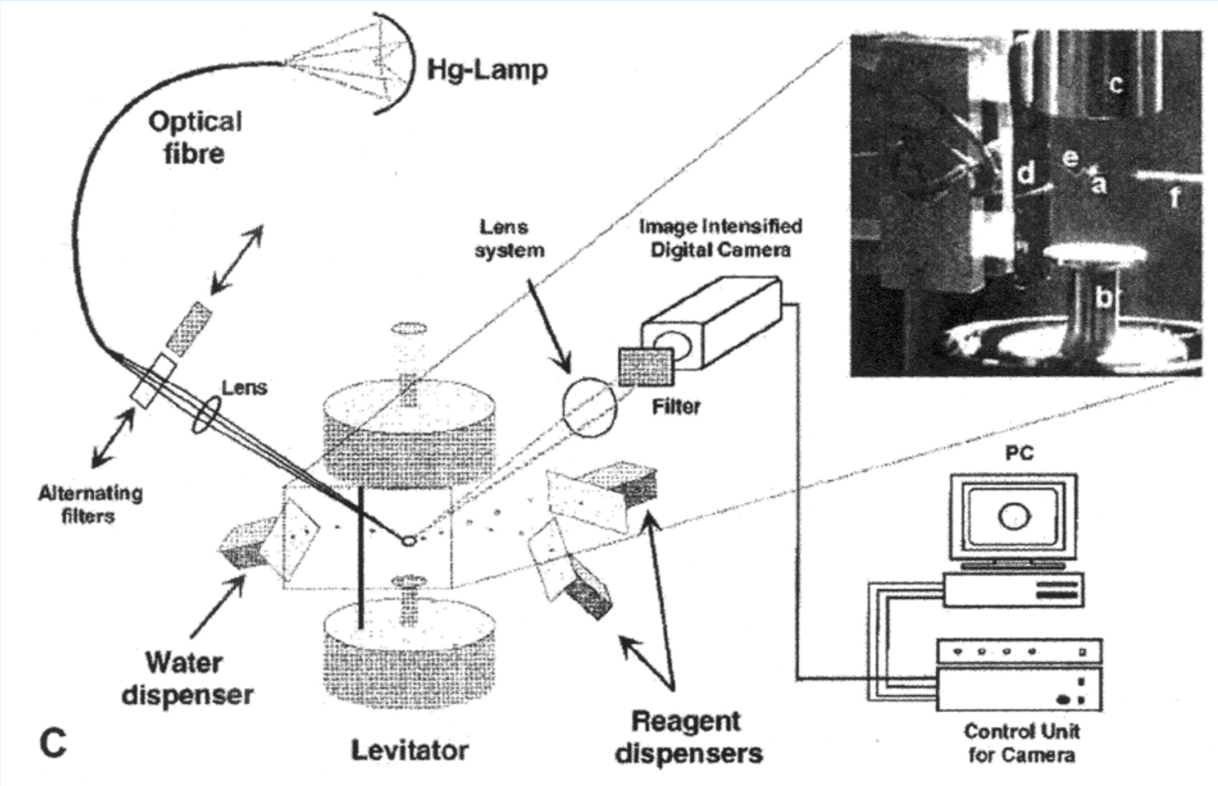
Acoustic levitator for bioanalytical applications at 0...70 °C, 100 kHz /7/



/7/ Santesson, M., Andersson, E., Degerman, T., Johansson, J. Nilsson, S., Anal. Chem. 72 (2000) 3412

3.1 State of the art : Environment

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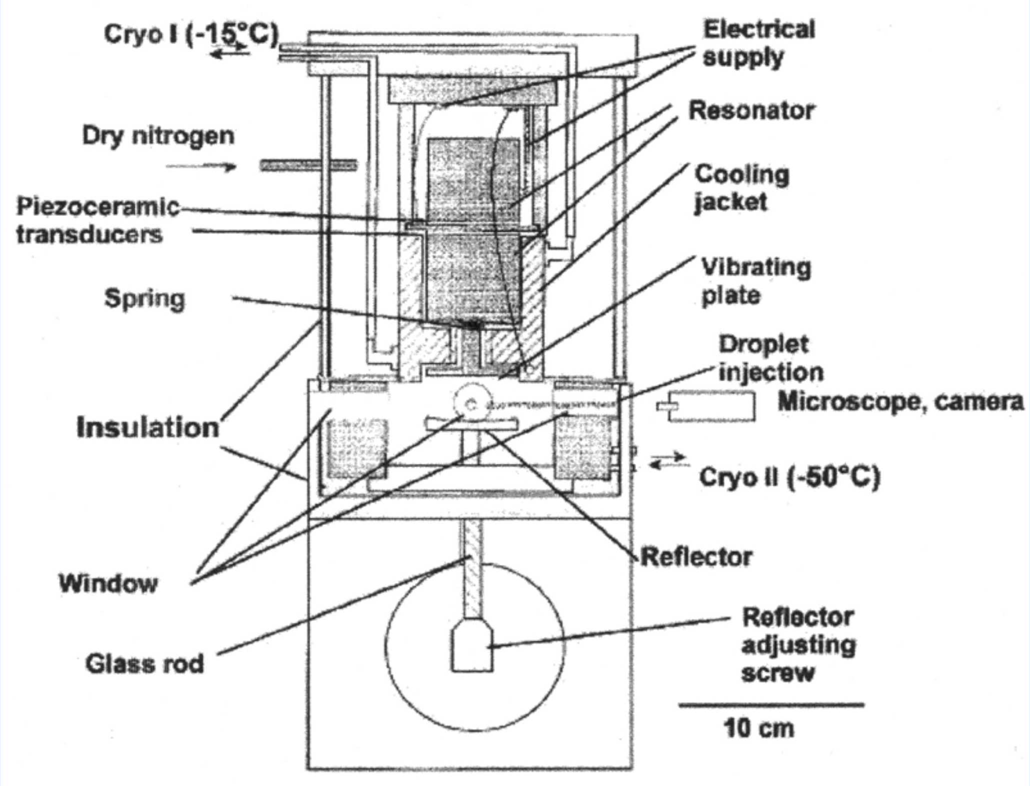
Upside down acoustic levitator for „cryo applications" -55...0 °C /8/



/8/ Jacob, P., Stockhaus, R., Hergenröder, D., Klockow, Fresenius' J. Anal. Chem. 371 (2001) 726

3.1 State of the art : Temperature range

main temperature range :	(approx.)	+15 °C ... +70 °C	(lamp)
extended temp. range :	(today, approx.)	-100 °C ... +80 °C	(cooled / heated gas)
highest temperatures :	(today, approx.)	+400 °C	(mirror furnace)

⇨ **Gas mixing systems /9/**

/9/ Lierke, E.G., Bessel-mode levitation in cyl. tubes at variable temperatures and pressures, Ultrasonics world congress 1995 proceedings, Berlin, Vol.2 (1995), 811-814

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→ **Gas mixing systems /9/**

→ **Hybrid levitators**

/9/ Lierke, E.G., Bessel-mode levitation in cyl. tubes at variable temperatures and pressures, Ultrasonics world congress 1995 proceedings, Berlin, Vol.2 (1995), 811-814

3.2 Capabilities : Hybrid levitators

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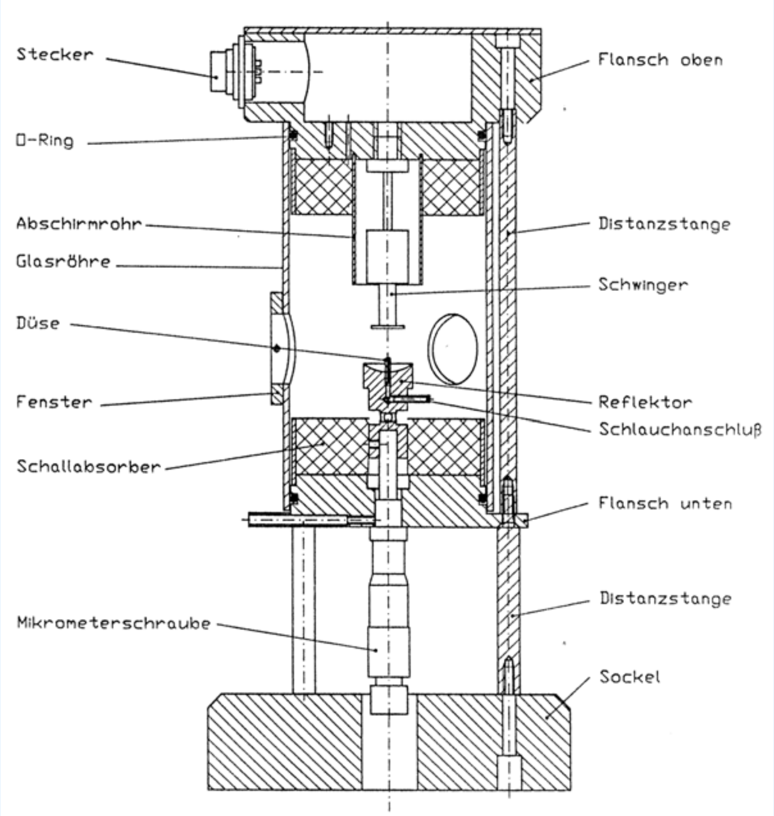
Aerodynamic-acoustic hybrid levitator /10/



/10/ Lierke, E.G., private communications

3.2 Capabilities : Hybrid levitators

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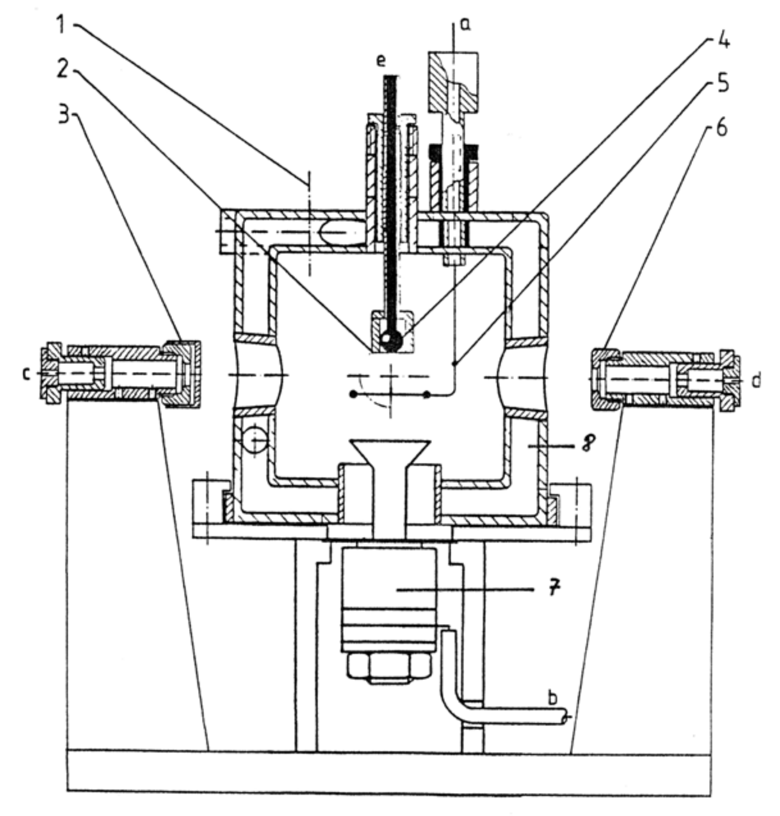
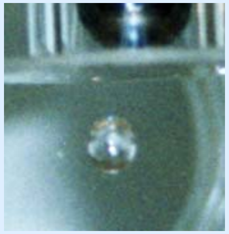
Electrostatic-acoustic hybrid levitator for controlled drop evaporation and condensation /2/



1 - temperature and humidity sensor
2 - sound reflector
3 - optical position sensor (6)
4 - field electrode
5 - charging electr.
7 - ultrasonic transd.
8 - process. chamber



electrostatically levitated 35µl water drop /2/

/2/ Holitzner, L., Diplomarbeit, FH Wiesbaden, Battelle Institut, Frankfurt/M., 1992

3.2 Capabilities : Further applications

- magnet field
- pressure

4. Engineering and design parmaters

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4.1 Soundfield : Vertical take off angle

The angle depends on :

- distance between transducer and reflector (number of pressure nodes, λ)

- sample position (position number of the pressure node)

- reflector diameter

- transducer diameter

4.1 Soundfield : Resonance amplification

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$$\left|\frac{v_{\max}}{v_{t,\max}}\right| = \cosh\frac{n\cdot\frac{z}{l}\cdot\pi}{2\cdot Q}\cdot\left(\sinh\frac{n\cdot\pi}{2\cdot Q}\right)^{-1}$$

Q – quality factor (= typ. 80...100)
n – number of pressure nodes
z/l – rel. position of the sample in the standing wave

Example :
Q = 81 (messured)
n = 5
sample in the 3rd pressure node : z/l = 0.5

$$\Rightarrow \left|\frac{v_{\max}}{v_{t,\max}}\right| \approx 10.3$$

typical for water drops @ 20 kHz:

v_{max} = 10 m/s $\longrightarrow$ $v_{t,max}$ ≈ 1 m/s

$A_t = v_{t,max}/2\pi f$ ≈ 8 µm

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Conclusion

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Thank you

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