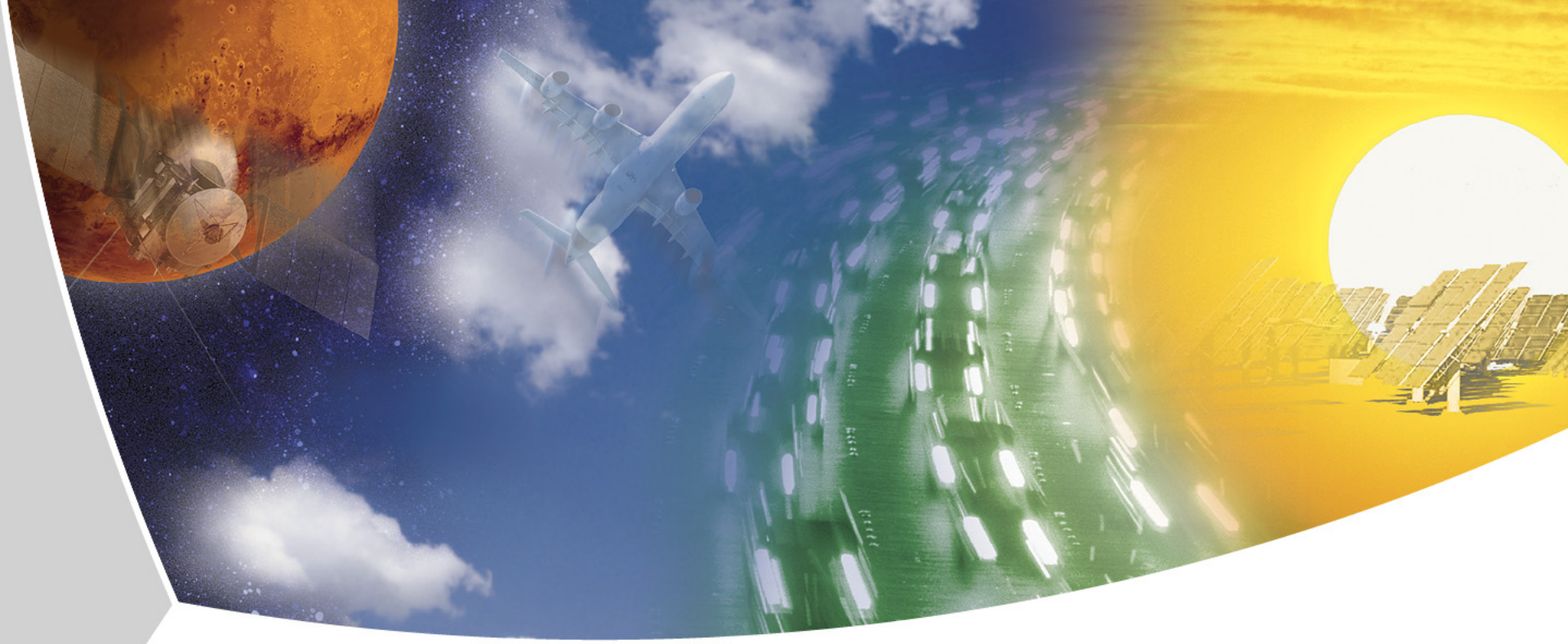


Inductive Measurement of Thermophysical Properties of Electromagnetically Levitated Metallic Melts

G. Lohöfer

Deutsches Zentrum für Luft- und Raumfahrt (DLR), Köln

AK-Thermophysik, Aachen, 10.03.15

Problems of liquid metal processing

High temperatures

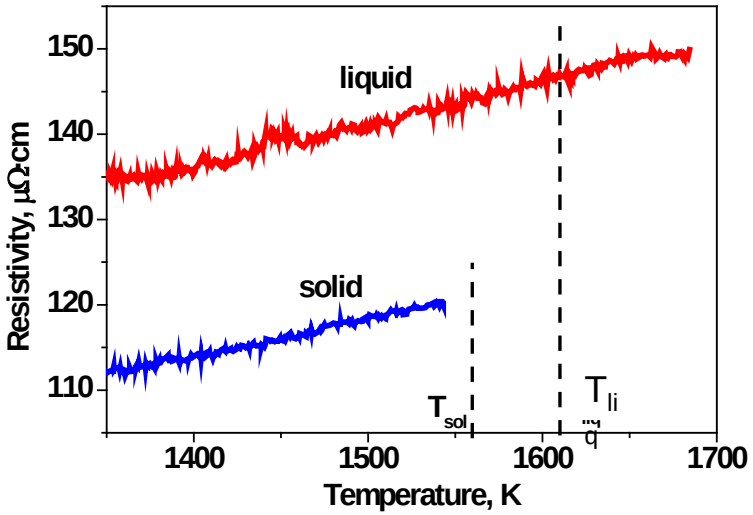
- **Chemical reaction**
- **Mechanical interaction** with crucible

- **High evaporation** rates

Undercooled temperature range

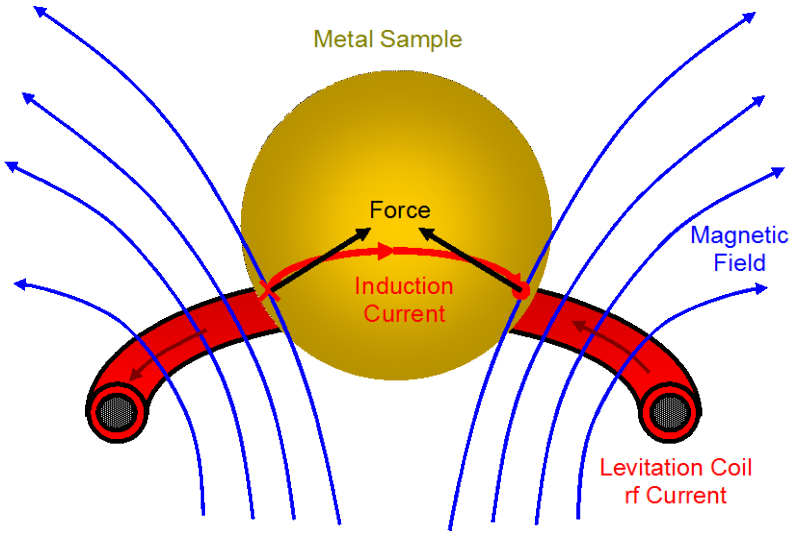
Contactless

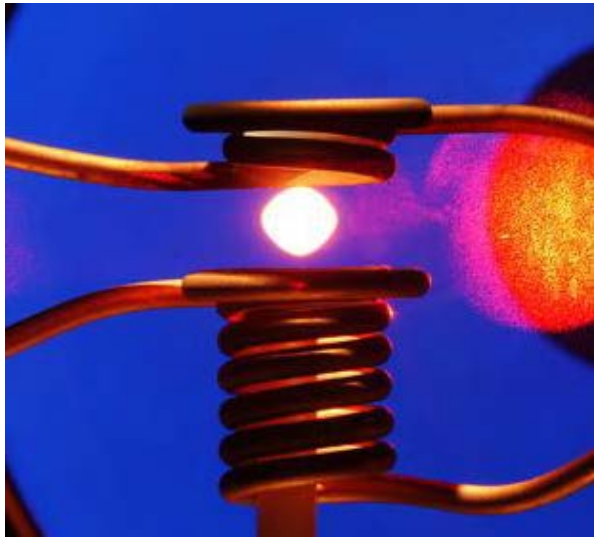
handling + measurement



Containerless metal handling

Electromagnetic levitation





RF magnetic field ⇒ Induction of **eddy currents** in metal sample (≈6mm)

~ 400 kHz

⇒ **Lorentz force** $\propto -\nabla B^2$ (equals sample weight)

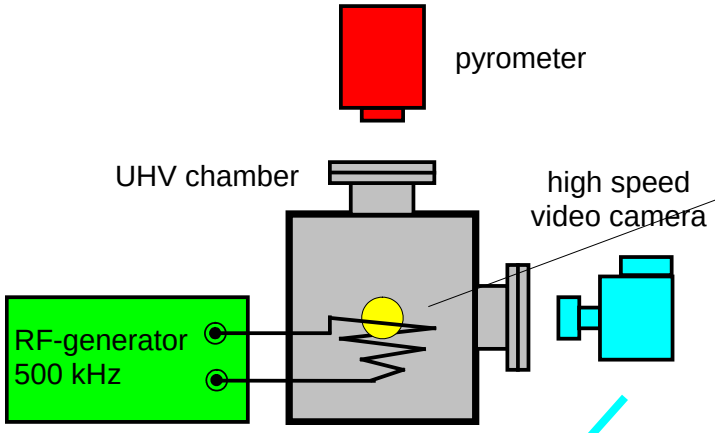
⇒ **Sample heating** $\propto B^2$

⇒ **Disadvantage**

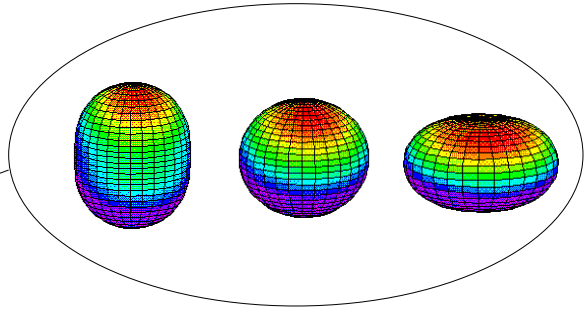
Deformation + stirring of the melt **!!!**

Contactless measurement method (surface tension)

Oscillating drop technique



Excitation of surface oscillations



- Oscillation **frequency** ⇐ **surface tension**
- Oscillation **damping** ⇐ **viscosity**

Standard evaluation

Image analysis ⇒ Frequency spectrum

⇓

Physical model

⇓

Surface tension

Problems: High **magnetic force**

⇒ **Non spherical** shape

⇒ Additional **surface force**

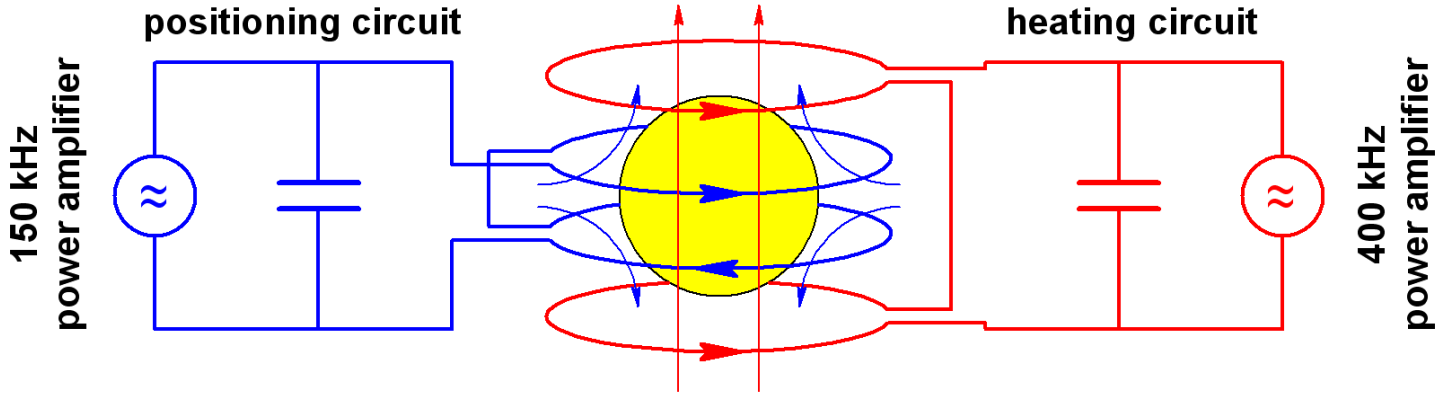
⇒ Magnetic **damping**

⇒ **Turbulent** fluid flow **damping**

Way out:  **Low gravity**

⇒ **low forces** ⇒ **simple, apparent** expt. environment

Low gravity levitation facility TEMPUS



rf magnetic **quadrupole** field
for **positioning** of droplet
$\mathbf{F \propto -\nabla B^2}$

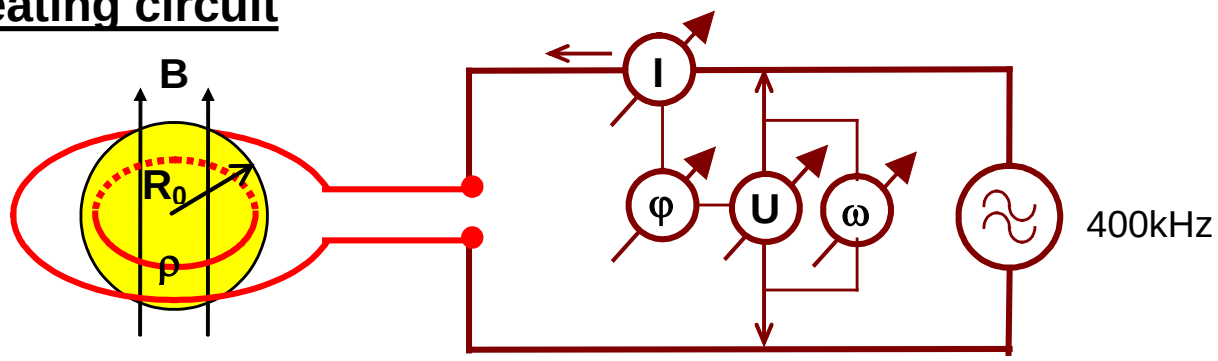
rf **homogeneous** magnetic **dipole** field
for **heating** of droplet
$\mathbf{P \propto B^2}$

Additional benefit:

can be used as **inductive measuring probe**

Inductive measurement: Principle

Levitation heating circuit



Coil impedance:

$$\underbrace{\frac{|U_0|}{|I_0|}e^{i\varphi}}_{meas.} = Z_{empty\ coil}(\omega) + Z_{sample}(\underbrace{\rho, Q}_{phys.}, \omega)$$

- Z_{sample}: **simple** function for **spherical** sample in **homogeneous** field
- **Two** equations for: ρ **:** electrical resistivity and Q**:** cross section

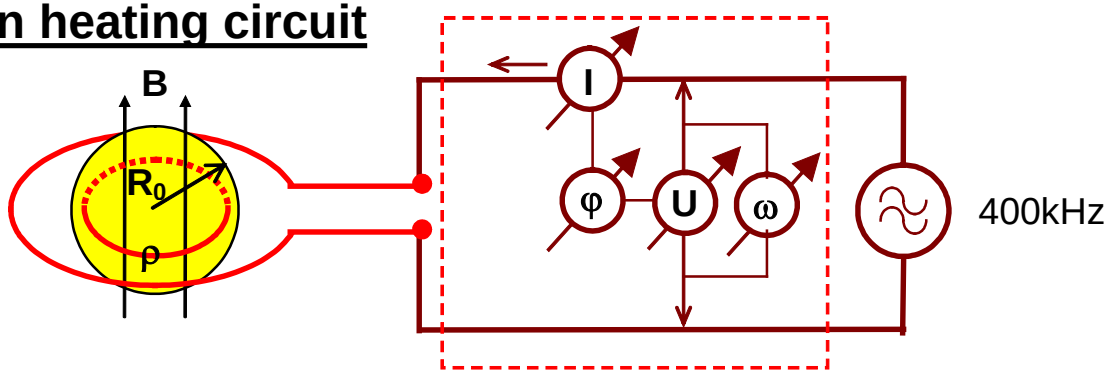
Required measurement resolution

$\Delta U_0/U_0 << 8\cdot10^{-4}$, $\quad \Delta\varphi << 0.15^\circ$

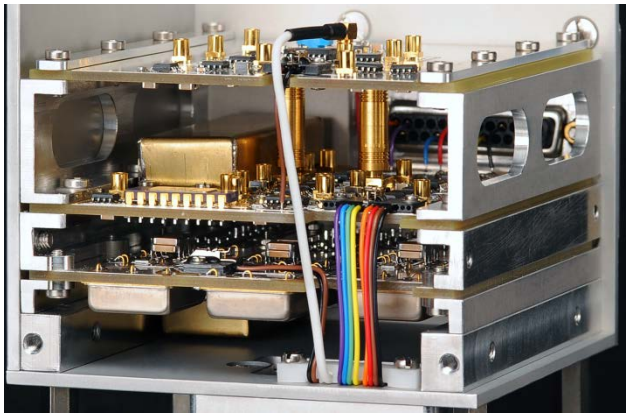
$\Delta I_0/I_0 << 8\cdot10^{-4}$, $\quad \Delta\omega/\omega << 2\cdot10^{-5}$

Inductive measurement: Realization

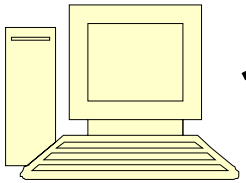
Levitation heating circuit



Measurement electronics



Data acquisition



- ADC
- Frequency counter
- Data evaluation

ρ : Electrical resistivity

Q : Cross section

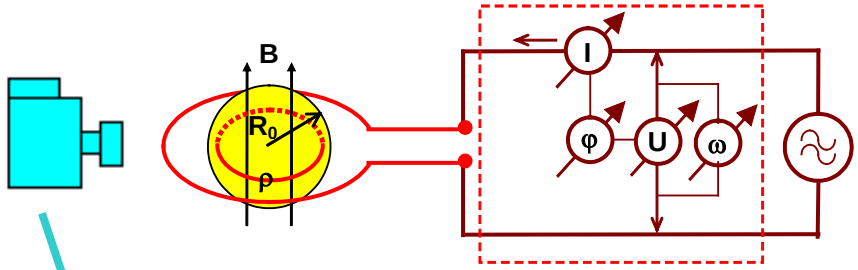
- Thermal expansion
- Detection of sample surface oscillations

Parabolic flight experiment

≈ 20 sec free fall (low g) time

Low g electromagnetic levitation TEMPUS

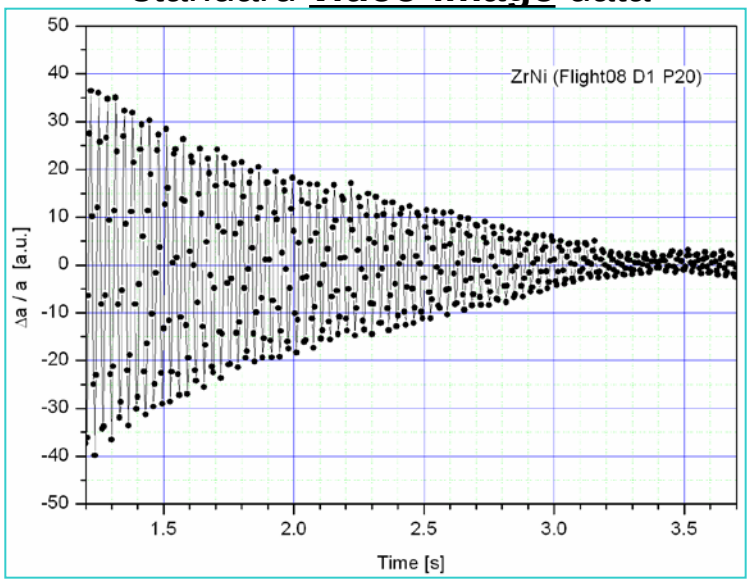
Surface Oscillations: Results from Parabolic Flights



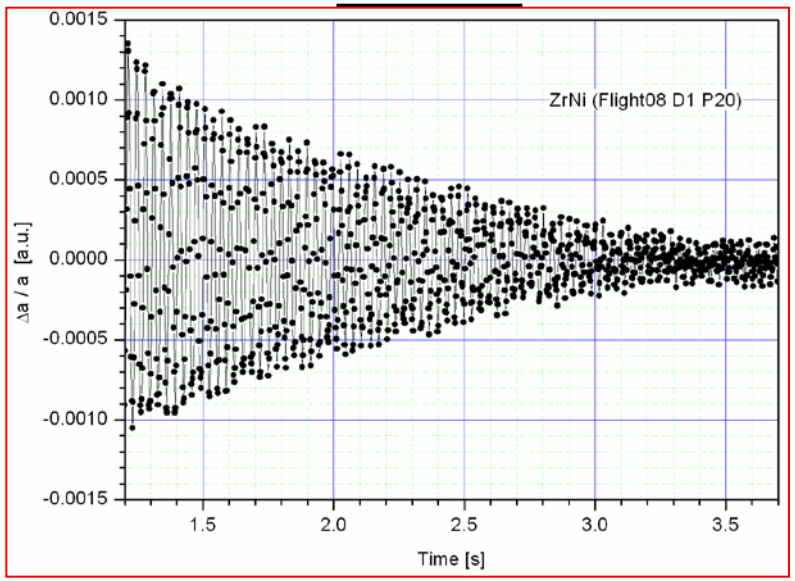
Damped surface oscillation of liquid sample

$$\Delta Q(t)/Q_0 = e^{-t/\tau}\,\sin(\omega t)$$

standard **video image** data



novel **inductive** data



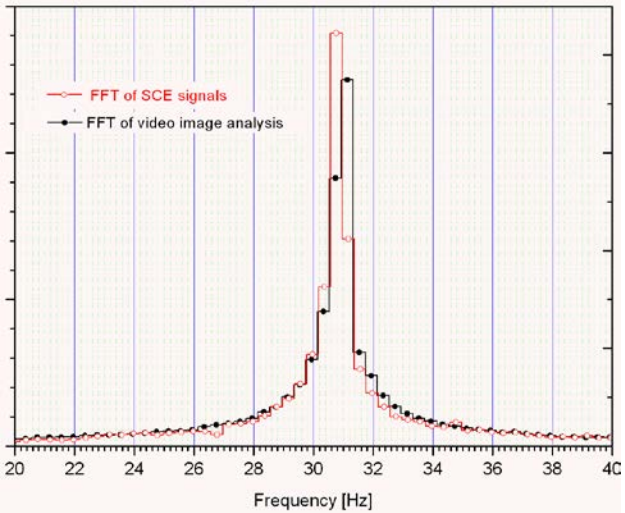
☹ Data handling, image analysis time consuming

☺ Simple data handling
☺ Online results
☺ High measurement rate

Comparison of datasets

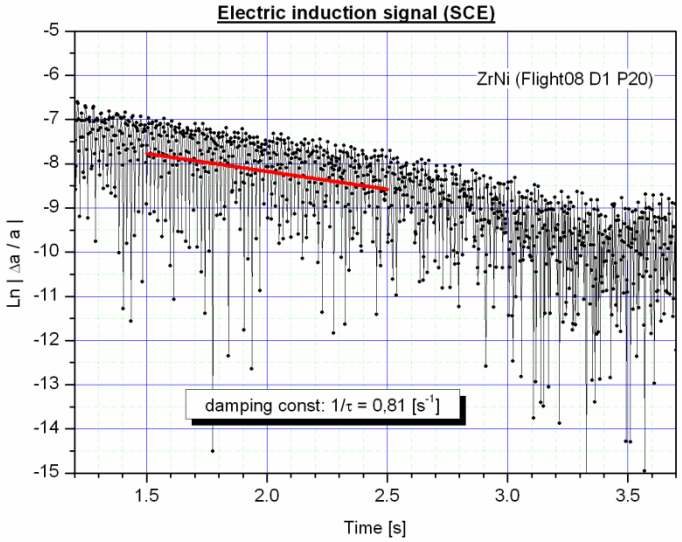
$$\Delta Q(t)/Q_0 = e^{-t/\tau}\,\sin(\omega t)$$

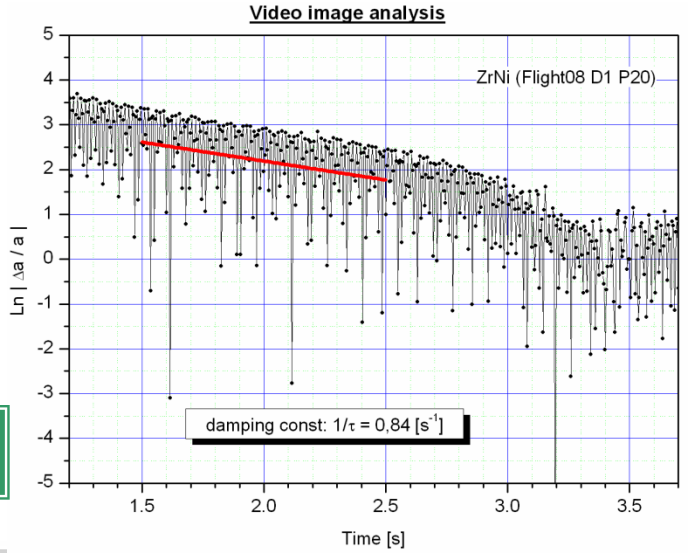
Frequency spectra (ω/2π)



☺ Frequency spectra identical within resolution band with of ±0.2 Hz

Damping (1/τ)

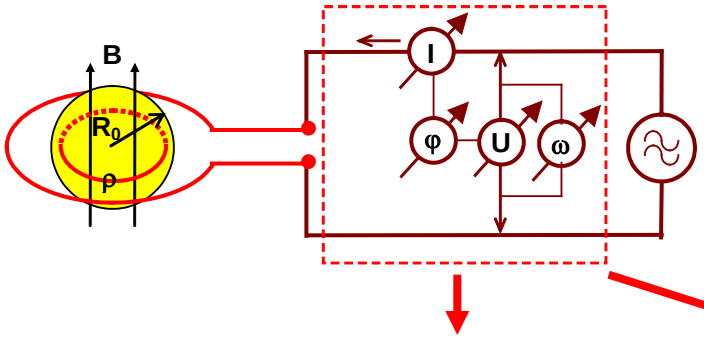




☺ Damping identical within 4%

Electrical Resistivity, Thermal Expansion

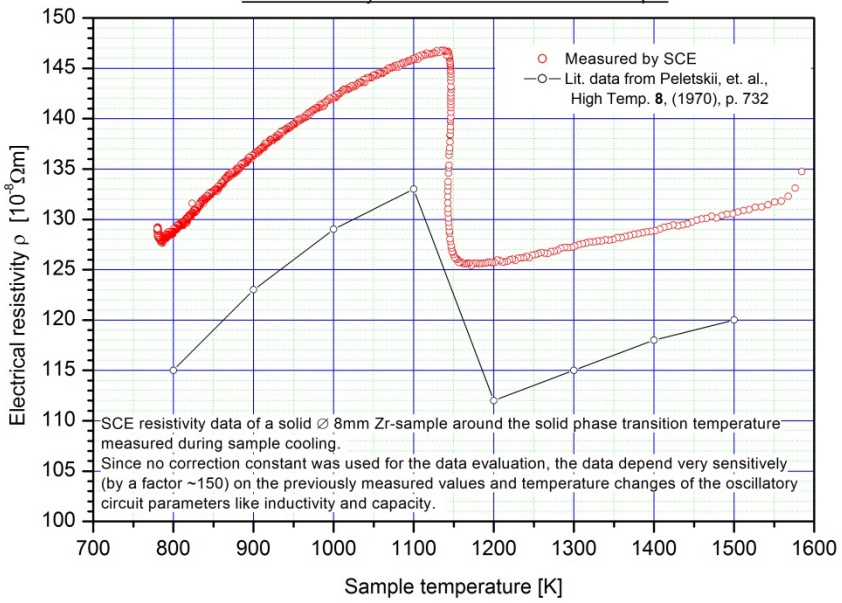
Results from ground tests on fixed, solid, spherical sample



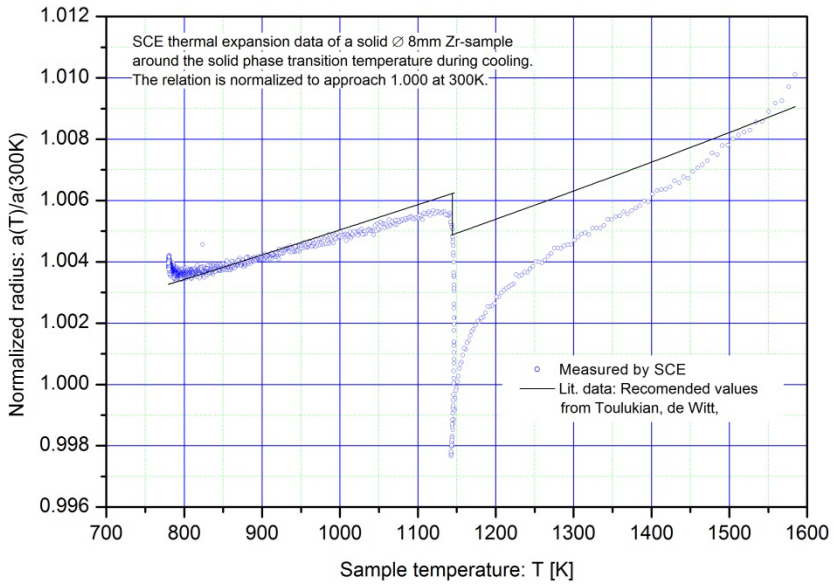
Resolution of meas. electronics

$$\Delta U_0/U_0 \approx 3\cdot10^{-4}, \qquad \Delta\varphi \approx 0.01^\circ$$
$$\Delta I_0/I_0 \approx 5\cdot10^{-4}, \qquad \Delta\omega/\omega \approx 5\cdot10^{-6}$$

"SCE-DM-upgrade" within TEMPUS Parab. Flight facility
SCE resistivity data for a solid 8mm Zr-sample



"SCE-DM-upgrade" within TEMPUS Parab. Flight facility
SCE thermal expansion data for a solid 8mm Zr-sample



Summary

- **Contactless** processing
  - ☺ No interaction of liquid sample with crucible
  - ☺ Enlargement of usable temperature range
- **Low g environment** ⇒ **low** magnetic **forces**
  - ☺ Spherical sample
  - ☺ Homogeneous field

  ⇒ Inductive meas. technique
- **Inductive** measurement technique
  - ☺ Contactless measurement of **resistivity**
  - ☺ Contactless measurement of **thermal expansion**
  - ☺ Contactless detection of **surface oscillations**

    compared to standard **video technique**

    ☺ Very low amount of data

    ⇒ Quick, online results

    ⇒ High measurement rate